CRANFIELD UNIVERSITY

HONGFEN LIU

A Structural Design Comparison of Metallic and Composite Aircraft Pressure Retaining Doors

School of Engineering
Aircraft Design

Full Time MSc
Academic Year: 2011 - 2012

Supervisor: Mr. P. Stocking
February 2012

CRANFIELD UNIVERSITY

SCHOOL OF ENGINEERING
by Research THESIS

MSC

Academic Year 2011 - 2012

HONGFEN LIU

A Structural Design Comparison of Metallic and Composite Aircraft Pressure Retaining Doors

Supervisor: Mr. P. Stocking
February 2012

This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

ABSTRACT

The pressure retaining door is obviously a sensible part of an aircraft, and the design criteria is much more critical than for the fuselage, so a problem caused by this critical criteria is the heavy weight of the door structure because it should be strong enough to withstand loads and stiff enough to meet the sealing requirements.

In spite of the pressure retaining door being so important, it is difficult to find design references. So, in this thesis, the pressure retaining door is investigated first, and then a typical structure of a type A door is selected as the study case using both metallic and composite material, in order to generate a standard method for door structure design, and to identify the key factors which can affect the structure weight.

The study indicates that the structure weight of a type A door can be kept in a range for different combinations of beams and stringers, and the composite door structure can be 20% lighter than the metallic door while the stiffness of the two doors remains similar. It is found that the skin contributes much more weight to the door structure than other components and the skin thickness is affected by the short edge of the skin panel divided by beams and stringers.

The results also found that it is much more serious when the end stop fails than when the middle stops fail.

Therefore, it appears that the composite door is a good material as an alternative to aluminium. Also the method of door structure design is reasonable for the composite door, although it would be better to consider the stiffness of beams while in the theory design period.

Besides IRP, the Group Design Project (GDP) is another important part of the MSc study; it lasts nearly half a year and we complete the Fly-wing concept design. The main contribution of the author to the GDP is the arrangement of doors, and also includes the family issues, cabin layout arrangement and a 3D model construct, which can be seen in APPENDIX B. According to the GDP

work, I will have broadened my professional knowledge and will have an overall view of aircraft design.

Keywords:

Pressure retaining doors, composite, structure, weight

ACKNOWLEDGEMENTS

The author would like to show her deepest appreciation to her supervisor Mr. P. Stocking, for his patient guides, helpful advices and supports

The author wishes to thanks her college LIU HONGQUAN, for the assistance of using FEM. and thanks also give to her colleague SHI ZHIJUN, who given her some help for using Matlab.

Thanks are extended to Aviation Industry Corporation of China (AVIC), and the sponsor-the China Scholarship Council, for given the precious opportunity of studying in Cranfied University.

Finally, the author would like to acknowledge the family for supporting in sprit during the whole year.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF GRAPHS

LIST OF TABLES

LIST OF EQUATIONS

NOTATION

ΔP	Working pressure load, MPa
N	Numbers of beam
n	Numbers of stringer
k_1	The rate of total load for end beams (B1)
k_2	The rate of total load for middle beams (B2)
M	The Bending moment of beams, N.m
$M_{\max}$	The ultimate Bending moment of beams, N.m
F	Force, N
$F_{\max}$	The ultimate shear force load on beams, N
q	Uniform load distribution on beams, N/m
h	Beam height, mm
L	Length of beam, mm
A	Area, m^2
t_1	Thickness of beam inner flange, mm
t_2	Thickness of beam web, mm
t_3	Thickness of beam outer flange, mm
t_4	Skin thickness, mm
I_{xx}	The second moment of area about axis xx
I_{NA}	The second moment of neutral axis
K	Column sub-matrix of curvatures of plate, m^{-1}
E	Young's Elastic Modulus, MPa
ε	Strain, m/N
f	Stress, MPa
f_b	Buckling stress, MPa
f_{xy}	Shear stress, MPa
f_{xyb}	Shear buckling stress, MPa
W_{Total}	Total weight of door structure, (without frame) kg

W_{Beams}	Weight of beams, kg
W_{Skin}	Weight of skin, kg
$W_{Stringers}$	Weight of stringers, kg
E_1	Longitudinal Young's Modulus, MPa
E_2	Transverse Young's Modulus, MPa
G_{12}	In-plane shear Modulus, MPa
υ_{12}	Major Possions Ratio,
X_t	Ultimate Longitudinal tensile strength, MPa
X_c	Ultimate Longitudinal compressive strength, MPa
Y_t	Ultimate Transverse tensile strength, MPa
Y_c	Ultimate Transverse compressive strength, MPa
S	Ultimate In-plane shear strength, MPa
ρ	Density kg/m^3
$e_{x,t}$	Ultimate Longitudinal tensile strain, %
$e_{y,t}$	Ultimate Longitudinal compressive strain, %
t	Laminate thickness, mm
E	Young's modulus, N/m^2
r	Ratio $\left(1-\upsilon^2\right)/0.91$ (when $\upsilon = 0.3$, $r = 1$)
υ	Possions Ratio

LIST OF ABBREVIATIONS

CU	Cranfield University
FAR	Federal Aviation Regulation
GDP	Group Design Project
3D	3-Dimensional
CATIA	Computer Aided Three Dimensional Interactive Application
AVIC	Aviation Industry Corporation of China
FAA	Federal Aviation Administration
FEM	Finite element modelling
FEA	Finite element analysis
COALA	College of Aeronautics Laminate Analysis
B1	end beams
B2	middle beams
ESDU	Engineering Sciences Data Unit

1 INTRODUCTION

1.1 Background

Doors of various size and shapes are a necessary part of transport aircraft, and are usually located in different areas of the fuselage. Some of the doors are located in non-pressurized areas and are therefore referred to as non-pressurized doors, such as the doors for inspection or maintenance. Some doors are located in the pressurized area, and these are called pressurized doors, such as the passenger doors and cargo doors. For the non-pressurized doors, the design criteria are usually simple as the problems of these types of doors can seldom lead to serious aircraft accidents. However, pressurized doors must conform to many regulations provided for the well-being of passengers, as the failure of these types of doors may lead to fatal accidents. The regulations are normally issued by an authorized agency, such as the FAA. For civil aircraft, not only should the design follow the regulations, but also the manufacture and testing should be regulated **[1]**. Actually, they are sensible components of the aircraft, as the pressurized retaining doors are moving components and located in the pressurized area. There are usually many problems involved in pressurized retaining doors, such as the flexibility of the mechanism, the leakage of the door. More importantly, the pressurized doors are related to the safety of the aircraft. Many aircraft accidents involving the failure of doors have been reported (the details will be specified in chapter 2.4). As a matter of fact, as moving parts of the aircraft, the doors as well as the flaps, ailerons and landing gears are usually among the most difficult design components of the aircraft. Door design is so difficult and specialized that most of the main civil aircraft doors of Boeing and Airbus are entrusted to the Euro-copter Company to design, as the company has many years' experience in door design. Although doors are critical and complex parts of the aircraft, it has been difficult to find a published reference book or material in order to conduct the door design systematically. So it is important to first investigate pressurized doors and to study the door design methods.

As mentioned by **[1],** the cut-out can highly resist loads, so the opening should be reinforced to carry the loads around with an additional structure. The weights of the structure for reinforcing the cut-out can be about three times the removed cut-out structure, while the weight of the door structure is also much higher than the removed cut-out structure. Additionally, the complicated mechanism is another heavy component of the door weight, and the door needs to be strong enough to suspend the door structure correspondingly, so the door usually seems to be very cumbersome. Therefore, to minimize the weight of the door structure should be a major objective of door design. As there is now a broad application of new materials in aircraft, manufacturers are also trying to use new materials for door structures in order to minimize the whole weight of the door. Besides aluminium, glare/honeycomb/FRP are materials that have been used. In this thesis, two door structures are designed with aluminium and composite using the same criteria for comparison.

1.2 Aim and Objectives

As the pressurized retaining door is an important part of an aircraft, only a few companies are specialized in its design and manufacture, so the correlation design references are commercial secrets which are hard to find. Other companies which are trying to design doors should invest much time and funds in research. So the investigation of different types and design criteria of pressurized retaining doors would be useful for conducting door design and would save money and time.

As mentioned in chapter 1.1, minimizing the weight of the door structure is a target of door design, so it would be reasonable to start by investigating a standard design procedure and studying the effects of a variety of factors on structure weight. Compared with cargo doors, the size of the cabin door is regulated by airworthiness as a standard type A, type B etc. As the load conditions are quite similar, the design method and design parameters should be quite similar and easy to follow. So, a typical type A door has been selected to be worked on, and the aluminium and composite material door structures are designed separately for comparison.

The details of the aim and objectives are divided into 3 parts:

1. Investigate the different types of pressure retaining doors, find out the common and different aspects of these doors, and survey past aircraft accidents involving failure of doors.

2. Undertake the study of a door structure design with aluminium, investigate the standard method of door structure design and the factors affecting the weight of the structure.

3. Undertake a study of the door structure design using composite, and compare it with aluminium.

1.3 Methodology

In this study, for both the theory calculation and FEM, FEA analysis methods are applied during the aluminium and composite door structure design.

The step of theory calculation is firstly to simplify the door structure into skin, beams and stringers, and assume a range number of beams and stringers for each combination of the structure, calculate the optimised weight of the structure, and then find out the best combination of lightest weight. Then construct the entire structure as a CATIA model which means including the skin, beams, stringers and frame to obtain the weight of each component. Matlab is used to calculate the optimised beam geometry of lightest weight.

Next, the step of FEM analysis is to construct an FEM model with Patran, and analyse it with Nastran, modifying the structure if necessary and comparing it with theory calculation.

During the composite structure design period, composite allowable stress and properties were calculated with COALA..

2 LITERATURE REVIEW

2.1 Requirements and recommendations for door design

Although many countries have their own airworthiness authorities and regulations, they are quite similar especially in door area. In this chapter, the FAR requirements for pressurized transport aircraft are mainly exposed, and some relevant recommendations founded in aircraft structure design references are also presented. In this chapter only some of the requirements and criteria related to door design are described.

2.1.1 FAR25 requirements

§ 25.365 Pressurized compartment loads

For airplanes with one or more pressurized compartments the following apply:

(a) The airplane structure must be strong enough to withstand the flight loads combined with pressure differential loads from zero up to the maximum relief valve setting.

(b) The external pressure distribution in flight, and stress concentrations and fatigue effects must be accounted for.

(d) The airplane structure must be designed to be able to withstand the pressure differential loads corresponding to the maximum relief valve setting multiplied by a factor of 1.33 for airplanes to be approved for operation to 45,000 feet or by a factor of 1.67 for airplanes to be approved for operation above 45,000 feet, omitting other loads.

(g) Bulkheads, floors, and partitions in pressurized compartments for occupants must be designed to withstand the conditions specified in paragraph (e) of this section. In addition, reasonable design precautions must be taken to minimize the probability of parts becoming detached and injuring occupants while in their seats.(DC-10accident)

§ 25.783 Fuselage doors.

(a) (1) Each door must have means to safeguard against opening in flight as a result of mechanical failure, or failure of any single structural element.

(2) Each door that could be a hazard if it unlatches must be designed so that unlatching during pressurized and unpressurized flight from the fully closed, latched, and locked condition is extremely improbable. This must be shown by safety analysis.

b) Opening by persons. There must be a means to safeguard each door against opening during flight due to inadvertent action by persons. In addition, design precautions must be taken to minimize the possibility for a person to open a door intentionally during flight.

(c) Pressurization prevention means. There must be a provision to prevent pressurization of the airplane to an unsafe level if any door subject to pressurization is not fully closed, latched, and locked.

§ 25.807 Emergency exits

(a) Type. For the purpose of this part, the types of exits are defined as follows:

(1) Type I. This type is a floor-level exit with a rectangular opening of not less than 24 inches wide by 48 inches high, with corner radii not greater than eight inches.

(2) Type II. This type is a rectangular opening of not less than 20 inches wide by 44 inches high, with corner radii not greater than seven inches. Type II exits must be floor-level exits unless located over the wing, in which case they must not have a step-up inside the airplane of more than 10 inches nor a step-down outside the airplane of more than 17 inches.

(3) Type III. This type is a rectangular opening of not less than 20 inches wide by 36 inches high with corner radii not greater than seven inches, and with a step-up inside the airplane of not more than 20 inches. If the exit is located over the wing, the step-down outside the airplane may not exceed 27 inches.

(4) Type Ⅳ. This type is a rectangular opening of not less than 19 inches wide by 26 inches high, with corner radii not greater than 6.3 inches, located over the wing, with a step-up inside the airplane of not more than 29 inches and a step-down outside the airplane of not more than 36 inches.

(5) Ventral. This type is an exit from the passenger compartment through the pressure shell and the bottom fuselage skin. The dimensions and physical configuration of this type of exit must allow at least the same rate of egress as a Type I exit with the airplane in the normal ground attitude, with landing gear extended.

(7) Type A. This type is a floor-level exit with a rectangular opening of not less than 42 inches wide by 72 inches high, with corner radii not greater than seven inches.

(8) Type B. This type is a floor-level exit with a rectangular opening of not less than 32 inches wide by 72 inches high, with corner radii not greater than six inches.

(9) Type C. This type is a floor-level exit with a rectangular opening of not less than 30 inches wide by 48 inches high, with corner radii not greater than 10 inches.

Table 2-1 Location and Size of Emergency Exits

type	size (height ×width) (mm×mm)	corner (mm)	step-up height (mm)	evacuation rate (person/90min)
I	1,220×610	203	floor level	45
Ⅱ	1120×510	178	floor level or 250	40
Ⅲ	910×510	178	510	35
Ⅳ	660×480	160	740	9
A	1829×1066	178	floor level	110
B	1829×813	152	floor level	75
C	1220×762	250	floor level	55

2.1.2 Recommendation Criteria

The recommendation design criteria below comes from reference **[1]**, which gives much more detailed load requirements of the door design than FAR, and some of the criteria are more critical compared with FAR. As the load criteria for the pressurized door is much stricter than the fuselage, it can be known that the pressurized retaining doors are in more serious condition than fuselage. In this thesis the door structure design follows these load requirements.

- **Design criteria**

The following criteria shall be used for the design and analysis of the fuselage plug-type door and non plug-type door.

(a) Design ultimate factor for pressure:

- Door structures shall be designed for 3.0 factors on pressure, for tension members and splices.
- All stop fittings, door latches and hinges shall be designed for 3.0 factors on pressure. Lateral loads on stops caused by friction shall be taken into consideration.
- Door structures shall be designed for 2.5 factors on pressure for shear and compression members.
- All door structures shall be designed for a negative 1.5 psi ultimate pressure acting singularly.

(b) design ultimate factors for flight loads plus pressure:

All door structures shall be designed for 2.0 factors on the maximum applicable operating pressure plus ultimate flight loads.

(c) flight loads acting alone:

All door structures shall be designed for ultimate flight loads alone when this is a critical condition.

(d) Flight loads shear distributions (for shear-type doors):

- 100% of the ultimate shear load shall be carried across the door (assume zero shear carried by fuselage cut-out).

- 2/3 of the ultimate shear shall be carried across the door with 1/3 being redistributed in the surrounding fuselage structure to account for wear, tolerances and misalignment.
- The effects of shear and pressure deformations of the door relative to the cut-out surrounding structure shall be taken into consideration for distribution.

(g) Door jammed condition:

The door structure shall not fail if the door becomes jammed and full actuator powder is applied.

(h) Design ditching pressures:

Design pressures for ditching shall be established during emergency landing on water surface.

(i) fail-safe design:

The door structure shall be designed for the failure of any single member. The fail-safe design pressure shall be a differential pressure times 1.5.

The table below shows a summation of those design criteria for pressurized fuselage doors.

Table 2-2 Design Criteria for Pressurized Fuselage Doors

Ref.	Design Condition	Component	Limit Load	Safety Factor	Ultimate Load	Remarks
(a)	Maximum operating pressure	Tension members	ΔP	2.5	22.5psi	
(a)		Door stop fittings and door latches	ΔP	3	27psi	lateral loads on door stops caused by friction shall be considered
(a)	Maximum relief valve pressure	Door structure critical in compression or shear	ΔP	2	18.8psi	
(a)	Negative pressure differential	Door structure	minus1.0 psi	1.5	minus1.5psi	
(e)	Ground gust operational loads: Door opening or closing	Door structure and actuation system	40 knot wind load	1.5	pressure	
(e)	Ground gust operational loads: Door open position	Door structure	65 knot wind load	1.5	pressure	
(e)	Random door loads	Door structure with door in any position			300 lb	Downward acting load
					150 lb	load in any direction
(f)	Emergency handle loads	Door structure, door handle & actuation system			451 lb 225 lb	
(f)	Emergency loads, opening only				2501 lb 400 lb	Roller load per latch Internal load applied by passenger
(i)	Fail-safe Internal plus aerodynamic pressure	Door structure and stops				
(i)		Internal pressure	ΔP	1.25	11.9psi	Design door structure for failure of a single member

2.2 Material

2.2.1 Introduction of metallic material [2]

The traditional metallic material of door structure is aluminium alloy, due to its high strength-to-weight ratio, it is classified into several series due to the typical alloying elements, and the commonly used in aircraft doors are 2000 series and 7000 series.

2000 series contain copper as the principal alloying element, which has a good durability and corrosion resistant ability, and they were once the most common aerospace alloys, and it is used for extruded shapes and forgings, the skin and sheet metal parts are usually applied this series. So, in this thesis, the skin, stringers and frame are applied the member of 2000 series 2014.

7000 series are alloyed with zinc, and can be precipitation hardened to the highest strengths of any aluminium alloy. It is widely used for highly-loaded parts. And normally it is used for beams and stops of the door. In this thesis, the beams also applied one member of 7000 series——7050 due to its high strength.

2.2.2 Introduction of composite material

The composite material has become one of the most popular materials of aircraft structure for their height strength and stiffness to weight ratio and other aspect of superiority structure properties, which can highly improve the structural efficiency. The advantages of composites compared with metallic include the ability of resistance to corrosion, and good performance of resistance to fatigue damage, which means can reduce the maintenance cost although the composite material is expensive. It is also can easily to produce the structure with complicated configuration, and can arrange the fibres orientation in the direction of strength/ stiffness need.

However, there are also a lot of disadvantages of composite material, including 'the poor energy absorption and impact damage ability, the degradation of structural prosperities under temperature extremes and wet conditions and the expensive and complicated inspection methods etc. **[3]**

Boeing and airbus has applied composite to design the A350 XWB **[4]** and B787 doors, Figure2-1 shows the composite passenger door of A350 XWB and cargo door of B787 doors. And it is reported the composite A350XWB door saves 30% weight than aluminium.

Figure 2-1 A350 XWB Passenger Door and B787 Cargo Door [4] & [5]

In this thesis, High Strength Carbon/Epoxy unidirectional prepreg is used for the door structure.

2.3 Door Investigation

2.3.1 Typical door type investigation

Figure 2-2 is the layout of Canadair Regional Jet 100/200—Doors**[6]**， which shows the general pressure retaining doors of transport aircraft, including the passenger door, service door, emergency exits, cockpit escape hatch and cargo door.

The size of the passenger door, service door and emergency exits is regulated by the Airworthiness (Table 2-1). Besides, the passenger door and the service door should also be used as emergence exits. Therefore, the size of the door structure should follow the standard requirement. Due to different requirements, the style and mechanism of the doors are different from pattern and function.

For the door, especially for the door structure, the design method can be similar, which will be investigated in the following chapters. As a matter of fact, the type of the aircraft doors can be generally classified into several kinds according to the style and mode of function. The typical types of doors are as follows.

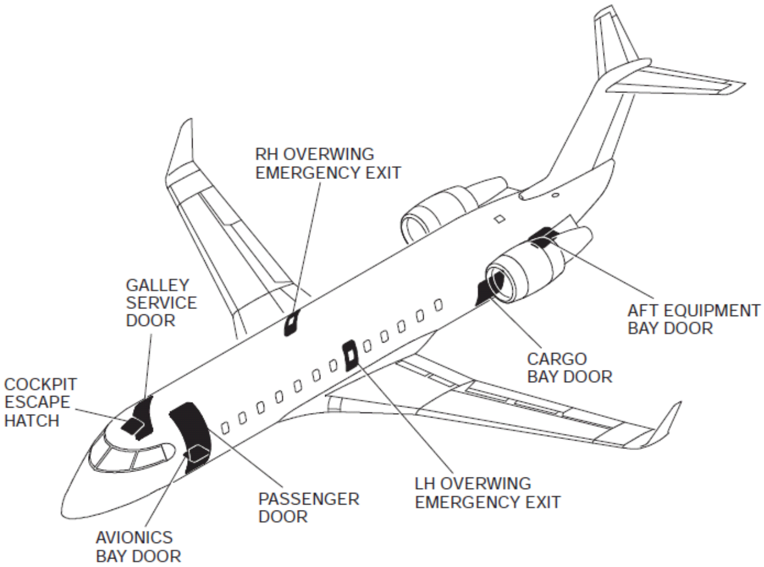


Figure 2-2 Layout of Canadair Regional Jet 100/200—Doors

(a) **Swing Opening Passenger Door**(B747)**[1]**

This type of door is commonly used in early Boeing aircraft, such as B737. An upper hinged gate and a lower hinged gate is designed at the top and bottom of the edge of this type door separately, which makes it possible to decrease the height of door when opening the door from inboard. The mechanism system is very complex as to control the moving of the door and the hinged gates simultaneously. It is usually opened forward, which can avoid being opened accidentally during flight due to drag load. Figure 2-3 shows the procedure of opening this type of door.

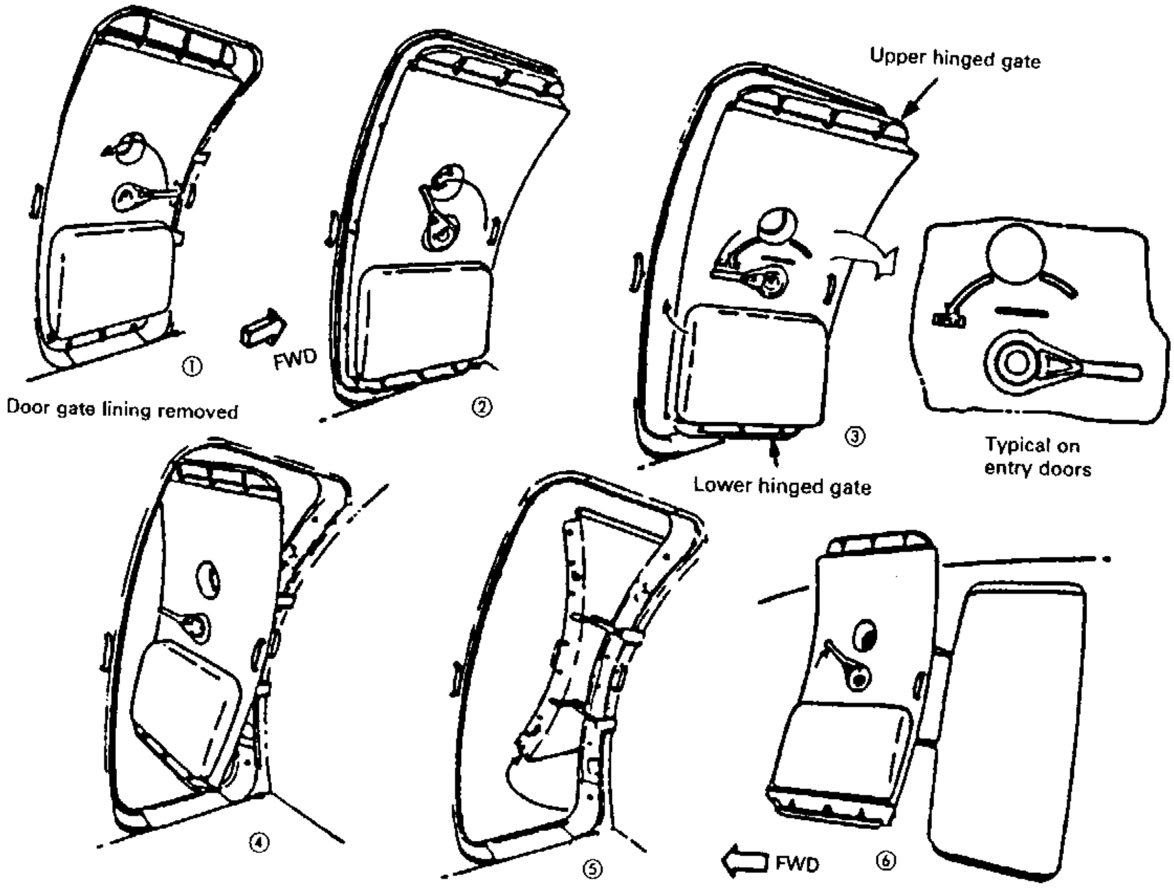


Figure 2-3 Swing Opening Passenger Door

This is a typical plug-type door, the advantage of this type door is the sealing performance is much better as the seal will be pressed tighter when pressure load increases, but the mechanism is much complicated since the upper and lower of the structure should be designed as part of the mechanism.

(b) **Horizontal Slide Opening Door** (Figure 2-4)

This kind of door is normally used in Airbus aircraft and later Boeing aircraft. It must be moved upward and inward first to make clearance with stops before it is opened or closed. The rollers guide the door to its closed place along the track of the cave. The tips of each beam are drawn back into the door and against the stops to prevent the air pressure with the rollers. The rollers are also designed to withstand the ditching and to minus the air pressure.

Figure 2-4 Horizontal Slide opening Door of B787 and B777 [7] & [8]

This kind of door could be called semi-plug door. The reason is that excepting for the stop which is located in the tips of the beam, the seal and the frame of the door are all in the outside of the fuselage frame. This is a popular type of door applied in modern aircraft for its simple mechanism. The demerit of this kind of door is leakage. As the displacement of the door structure increases because of the cabin pressure load increasing, the sealing clearance becomes larger, especially in the upper and lower area where the stiffness is usually weak, so the leakage is quite common.

(c) Inward Slide Opening Door

This type of door has been used on the L-1011, DC-10, B767, etc. When opening, it should be firstly moved inward and slid upward on rollers (Figure 2-5). As for some exception, it should be slid forward or afterward. Normally, this type of door is operated by electrical equipment either inside or outside, although it can also be opened manually in consideration of emergency situations or electrical power lost. The advantage of this type of door is that it can avoid the affect of weather as well as the damage possible made by loading equipment when the door moved inside. However, the mainly disadvantage is that it needs some inner space of cabin for operation. Besides, the operation system is very complex. So, it is rarely used in commercial aircraft, and mainly used in military transportation aircraft for certain usage.

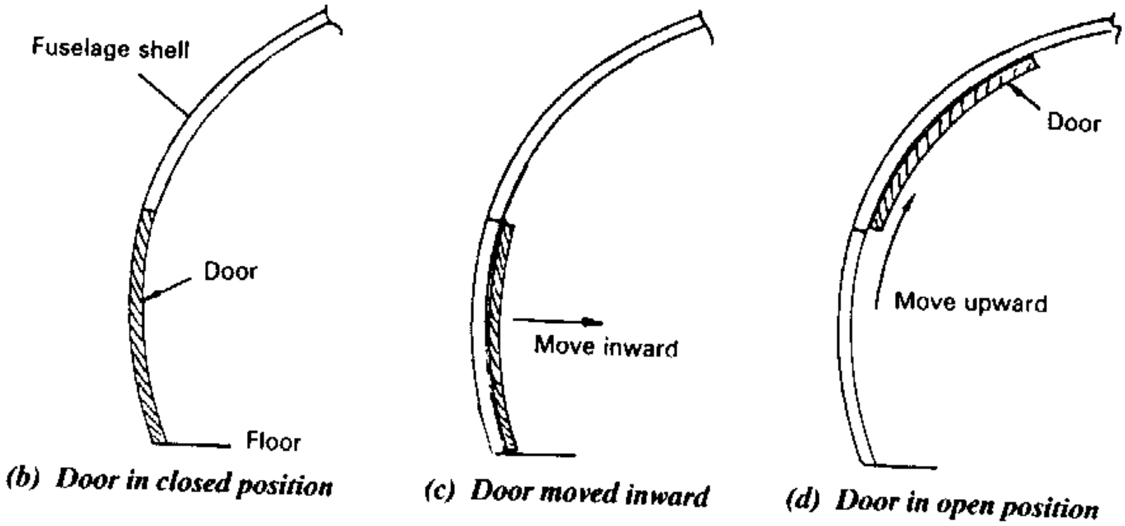


Figure 2-5 Inward Vertical Slide Opening Door [1]

(d) Door without hinge

This kind of door is usually used as emergency exit only (Figure 2-6). And the size is usually small so that it is light enough for a person to lift it up and move it away. As it is seldom opened but for checking or maintaining or in emergency cases the mechanism system is normally designed as simple as possible to reduce the weight. Because the hinge which used to attach the door to the fuselage contributes the main weight to the mechanism so it is cancelled and it just uses latches to hold the door in its closed position. During flight, the air pressure can press it on the fuselage frame safely because the door structure is larger than the cut-out.

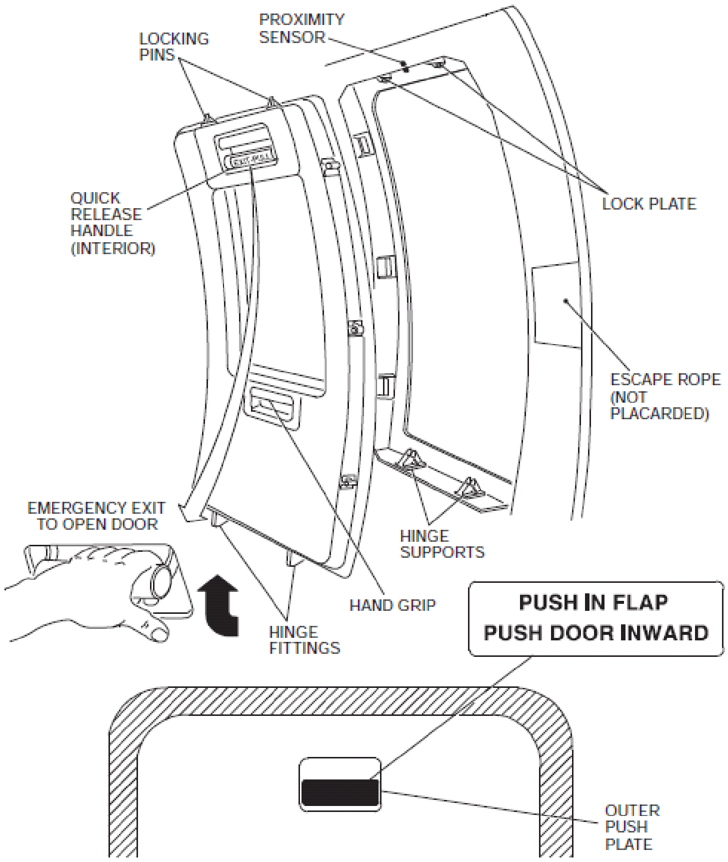


Figure 2-6 Door without Hinge [6]

(e) Door Incorporate with Air-stair[5]

Some of the aircraft is designed to incorporate integral stairs with a retractable lower step and folding handrails. The door is hinged at the cabin floor level and opens outward (Figure 2-7). This kind of door can replace the moving staircases to let passengers board or depart the cabin. It is normally in small regional airliners and aircraft which operate into less-well equipped airport and for the Ventral exit is usually designed as air-stair.

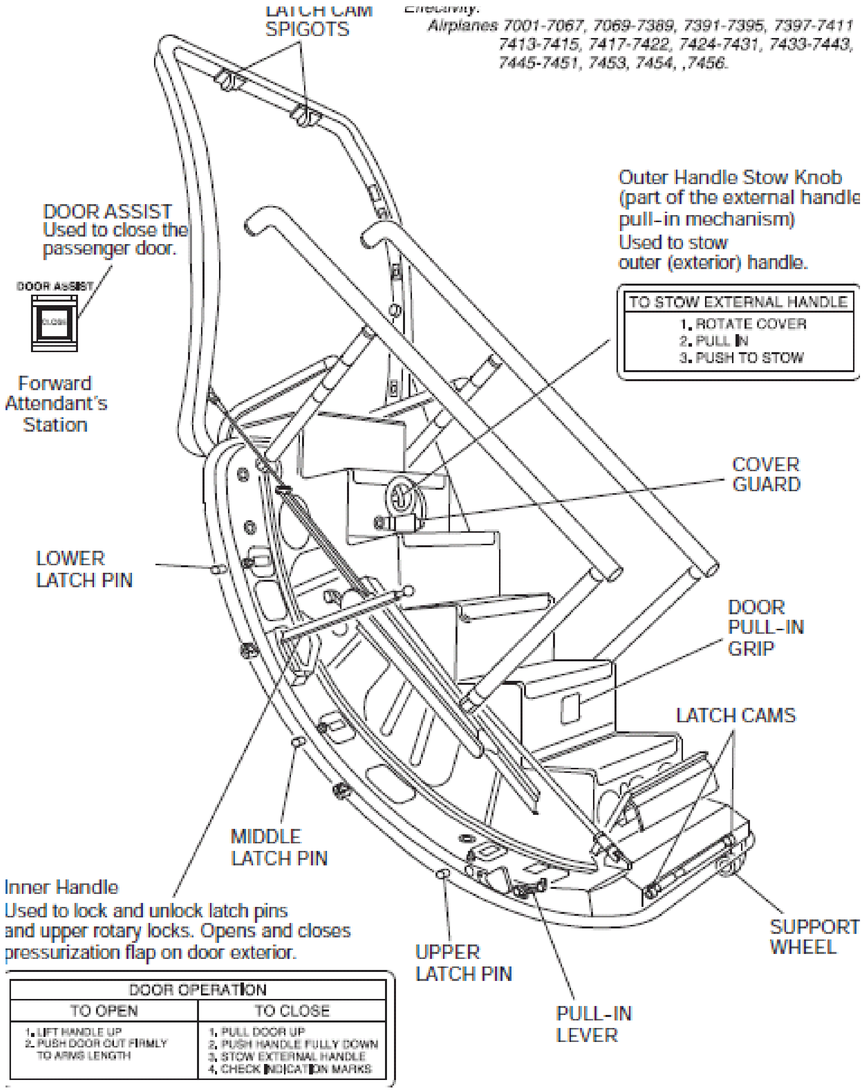


Figure 2-7 Passenger Door incorporate Stair

(f) Cargo Door

The size of the cargo door is not regulated by the airworthiness as the cabin door. It is designed to accommodate the freight and standard container requirements. Normally, both main huge cargo doors and bulk cargo doors are included in transport aircraft. The main cargo doors usually belong to the outward opening type as it can save space for freight, and the bulk cargo doors are often designed as the inward opening type for consideration of safety and sealing. The structure and mechanism of the main cargo door and bulk cargo door are quite different. Figure2-8 illustrates the typical cargo door arrangements. Figure 2-9 shows the mechanical system of a typical main cargo door.

1) Outward opening type

2) Inward opening type

3) Downward opening type

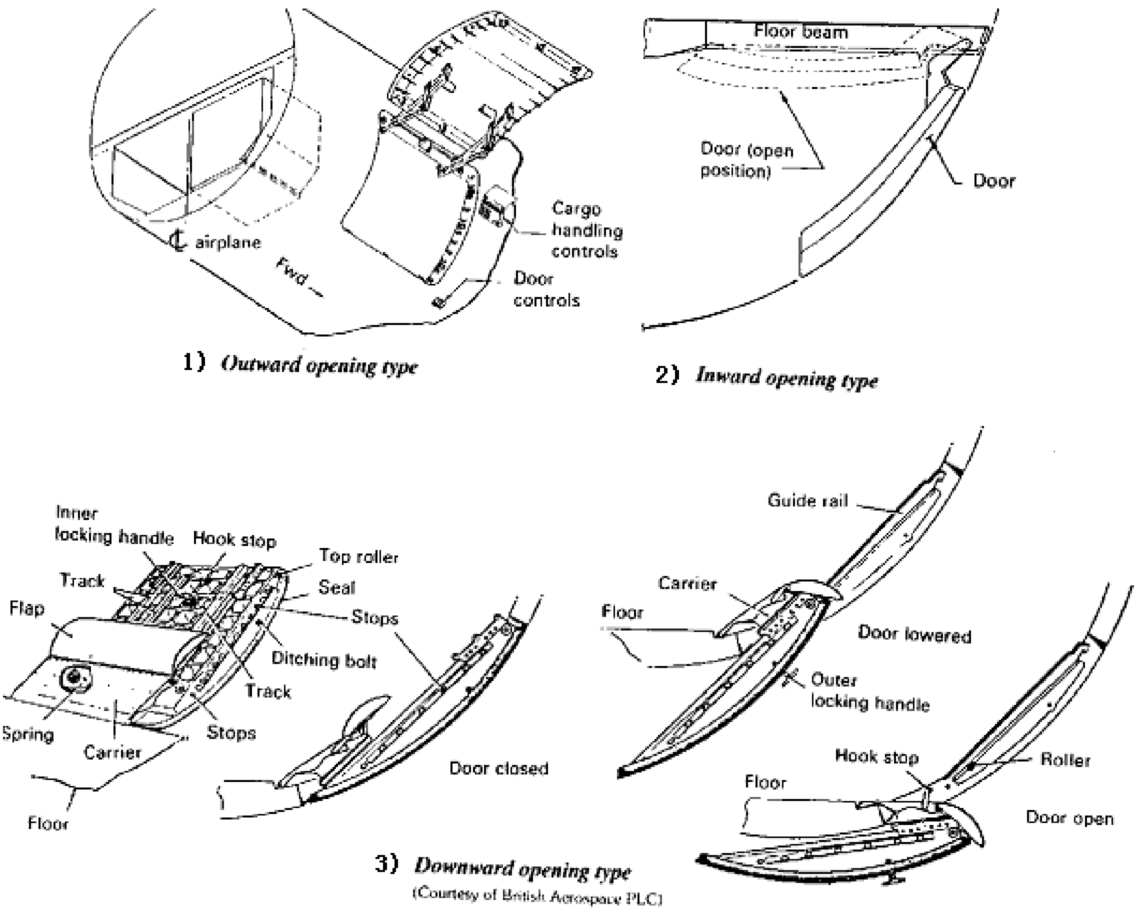


Figure 2-8 Cargo Door Arrangements [1]

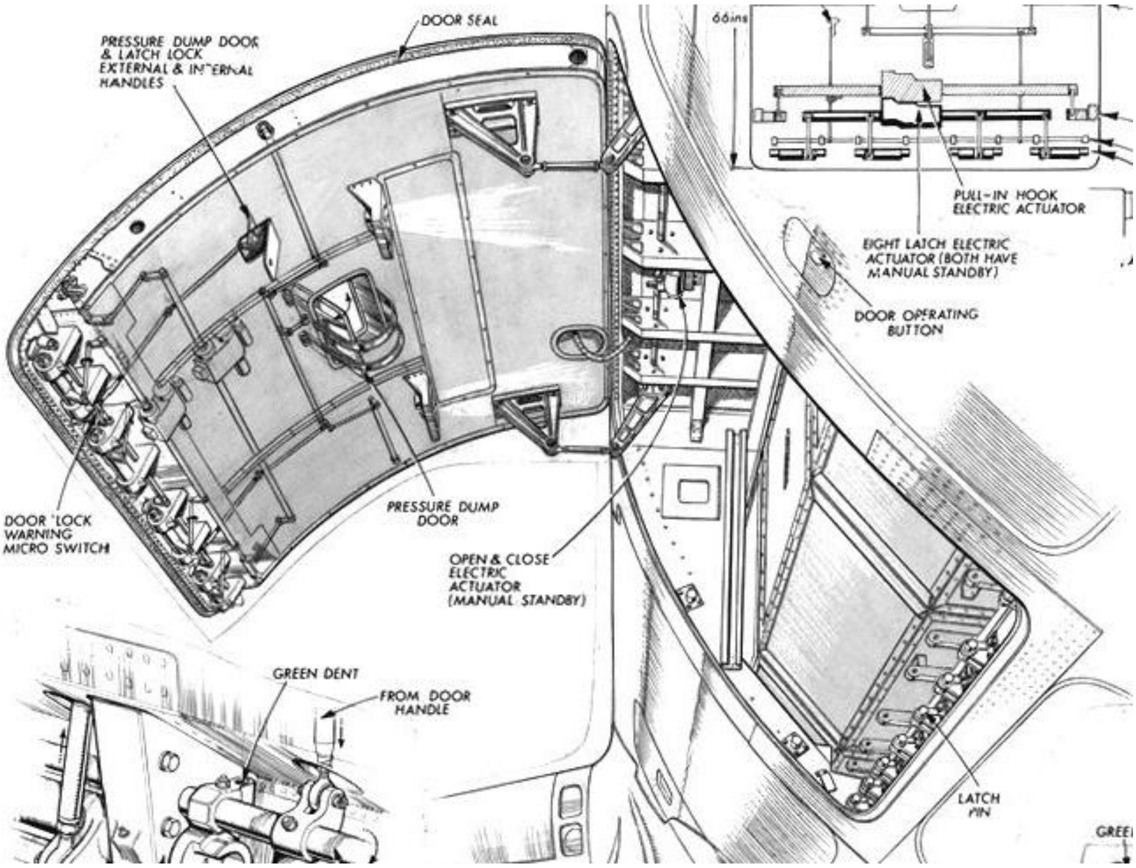


Figure 2-9 L-1011Foward Cargo Door[9]

2.3.2 Door classification

Although the function and operation of aircraft pressure retaining doors seems to be diversity, it can be generally divided into two types, plug-type doors and unplug-type doors.

Plug-Type door

The type (a) 、 (b) 、（c）、（d）、（e）、（f）which are just mentioned in Chapter 2.3.1 can be all treated as plug-type doors because they have the same load-carry ability and the structure arrangements are quite similar. Figure 2-10 shows a typical structure of plug-type door. Normally, it includes the outer skin, frame, beams, and sometimes some stringers are designed to connect the beams to keep the door configuration along with frame and to divide the skin into small panels to reduce the stress and displacement of the skin. For doors of this type, the structure is usually larger than the cut-out, and when closed, the door moves into the inside of the fuselage and is pressed against the cut-out.

For plug-type doors, they usually carry the inertial loads and air pressure loads, and it is designed to withstand the air pressure different with the door structure against the fuselage frame. However, the mechanism is not taking part in withstanding load. The pressure differential load on the door is transferred in the course direction to the fuselage, from the skin to the beam and then from the tips of the beams which is called the stops to the fuselage frame. In this type of door, the skin and the outer side of the beam are carrying tension load, the inner side of the beam takes the compression load, and the web of beams takes shear load.

The doors in the pressurized cabin are often designed as Plug-type door, because the safety is much better than unplug-type, since the interior air pressure is normally higher than exterior during flight and it can hold down the door in its place and prevent accidental opening.

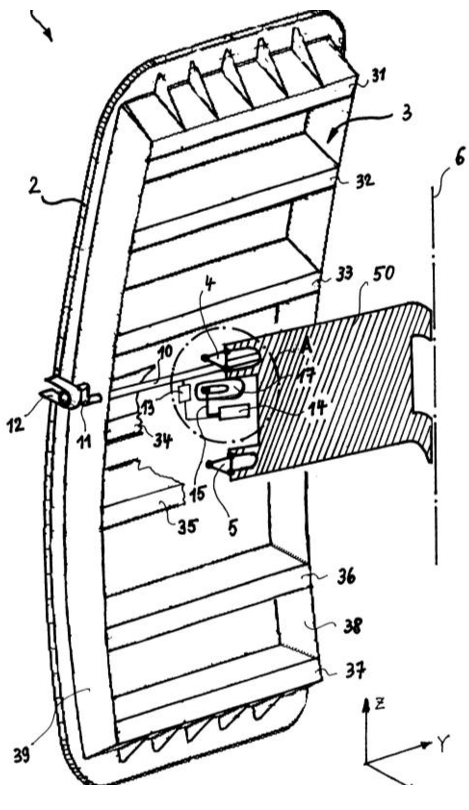


Figure 2-10 Structure of Plug-Type Door [10]

Unplug-Type door

The outward opening cargo doors are generally designed as unplug-type. The reason is that the main cargo doors are usually should large enough to make clearance for standard containers loading. If the door is designed as inward opening plug-type, it will occupy lots of space for operating the door. Besides, if it is designed as outward opening plug-type door, it would waste a lot of weight on mechanism as it should be stronger enough to lift the heavy door structure.

The structure mechanism of unplug-type doors and the way of load-carry are quite different from plug-type doors. As Figure 2-9 shows, the upper edge of the door is attached to the fuselage with a series of piano hinge; the lower edge has some hooks which are part of the mechanism system. While closing the door, the hooks rotate to clasp the pins in the fuselage, which makes the door in closed position. The beams of the unplug-type door structure are in the vertical direction. Figure 2-11 illustrates the structure of a cargo door. The hooks are just located on the tip of these beams.

Figure 2-11 Structure of Cargo Door [11]

2.4 Accidents Investigation Involving Doors

It is reported that a lot of aircraft accident involved the problems of doors. Some of the problems can cause the plane can't flight on schedule. For example, some doors are reported leakage because of the passenger moving the door inadvertently or in purpose, which caused the airliner have to fly back. Some problems relate to doors also can cause fatal issues. Several such accidents involving doors are listed as follows:

1) June 12, 1972(DC-1O): American Airlines Flight 96 lost its cargo door after took off a few minutes and caused the cabin floor collapsed. [12]

2) March 3, 1974(DC-1O): An identical cargo door blow-out caused Turkish Airlines Flight 981 to crash, and 346 deaths. [13]

3) 12 March 2004(Dornier 328-100): The passenger door of Dornier 328-100 aircraft had flew open when it was preparing for takeoff from Scotland's Edinburgh Airport. [14]

4) February 24, 1989(B-747): United Airlines flight 811, a Boeing 47-122.experienced an explosive decompression, the forward cargo door was lost in flight over the Pacific, and a large part of the pressure hull at cabin level with 9 seats was ripped away in separating the door. Figure 2-12 shows the Cargo hole of light 811. [15]

According to investigation, most plane accidents are involving the mechanism of doors, because of which lots of airworthiness requirements are regulated for the mechanism system. However, for the plug-type door, the failure of the mechanism may only cause schedule problems because the pressure load can press the door in the fuselage. While for the unplug-type door, the failure of the mechanism may cause fatal accidents, because the suddenly opening of the door can cause fuselage blast, like accident of Flight 981.

Although the mechanism is an important part relate to door safety problems, the structure should also be strong and stiffness enough to sustain the pressure load and reduce displacement. Besides, for the unplug-type and semi-plug type doors, the displacement of the door structure could cause leakage as the pressure load increases.

Figure 2-12 United Airlines Flight 811 Cargo hole [15]

3 TYPICAL DOOR FOR CASE STUDY

According to the investigation of different pressurized retaining doors, the structure of horizontal slide opening Type A door was selected as a study case. The reason of selecting a Type A door as the author's target is as follows:

Firstly, as the size of the cabin doors is regulated by airworthiness, according to investigate one of the standardized doors, it would be meaningfully to form a standard design process and find out the main factors of door design, which can be used to conduct other standardized door design of structure.

The reason for choosing the horizontal slide opening Type A door is that the rate of using this type doors is much higher than other types, especially for large or wide-body aircraft, such as the Boeing and Airbus passenger doors of civil aircraft. As investigated, it is known that most of Airbus passenger doors applied this type, and for Boeing aircraft, although the Swing Opening passenger door was adopted in most of previous aircraft, the Horizontal Slide Opening door is preferred in B777/B787 now.

The advantage of this kind door is that the mechanism is simple and flexible, and it is convenient to operate it. However, the disadvantage is that because of its seal format, as Figure 3-1 illustrates, the requirement of door structure stiffness is more critical. As the seal actually is in the outside of the fuselage, when the deformation of the structure increases as well as the pressure load, the leakage would be much more sensible than other type cabin pressure doors, especially in the upper cantilever area. Therefore, if the structure is designed much conservative to comply for the stiffness criteria, not only the weight of the structure will increase, but also the weight of mechanism, as it is need to be intensive and stiffness enough to sustain the whole weight of the door. So that according to study the structure of this type door, it is necessary to work out the effect of the parameters to the weight of the door structure, and the stiffness of the door which can give some guide on sealing design, and also it is important to study the structure with composite material which would be able to reduce the door structure.

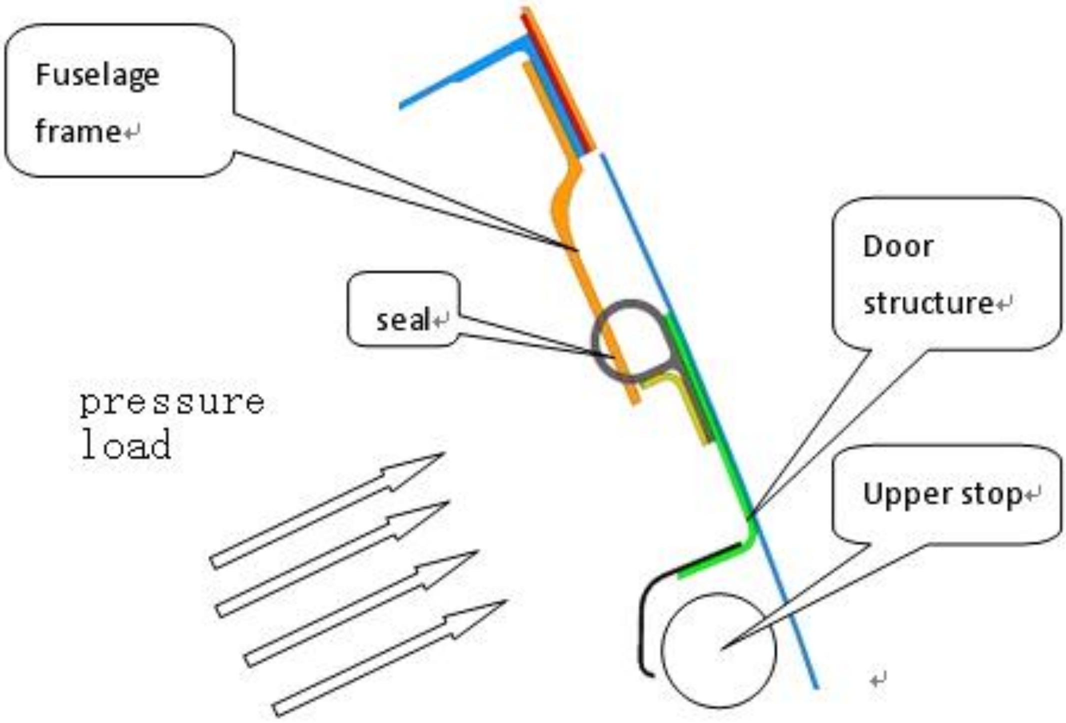


Figure 3-1 Upper Seal Type of Horizontal Slide Opening Type Doors

3.1 The geometry of the door

As located in different area and different aircraft, the outer configuration of the same type of door maybe vary, but actually the effect of the configuration to door structure is very limited. So in this study, for easy and accurate study consideration, the door is assumed to be located in the parallel area, and according to investigate different wide body aircraft (Table 3-1), the parallel fuselage geometry apply the average diameter 5.608m.

It can be seen from Table 2-1 that the Type A door clearance according FAR is 1829×1066mm. As a matter of fact, the door structure should be a little bigger than this because some extra area should be reserved for installing seal. At last, 25mm wide space was assumed to be used for seal, and as also considering the effects of the fuselage curve, the door size is determined as1900×1120mm, as Figure 3-2 shows.

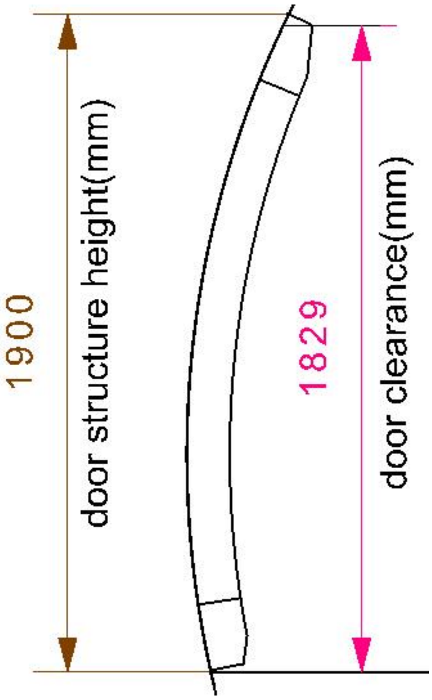


Figure 3-2 Door Size

Table 3-1 Fuselage Diameter

Type	Wide body fuselage diameter(m)
A330	5.64
A340	5.64
A350	5.96
B767	5.03
B787	5.77
average	5.608

3.2 The format of the door structure

The structure of this type door normally consists of the frame, the stop, the beam, the outer skin and sometimes the stringer and inner skin, as Figure 3-3 shows. The door structure usually has higher density of beams and stringer than fuselage frame because of its more critical load requirement. And the beams are the primary member that takes the main load, while the stringers are normally separated into several segments which are mainly used to sustain the beams as well as transfer the loads from the outer skin to the beams. Other roles of the stringer are to divide the skin into small panels to reduce the maximum stress and to displace the skin, which also helps to keep the figure of the door structure. Normally, two methods are used to ensure the continuity of stringer segment, one is connecting the stringers to the beams directly, and another is connecting them to the beams with a connection board, like figure 3-4 shows.

As the pressure load is mainly taken by beams and skin, so in the theory calculation stage of the door structure design and analysis, the load carrying member of door structure is only simplified into beams and skin, and the stringer is only treated as the sustain component. For more conservatively consideration, the beam is treated as free (simple) beams.

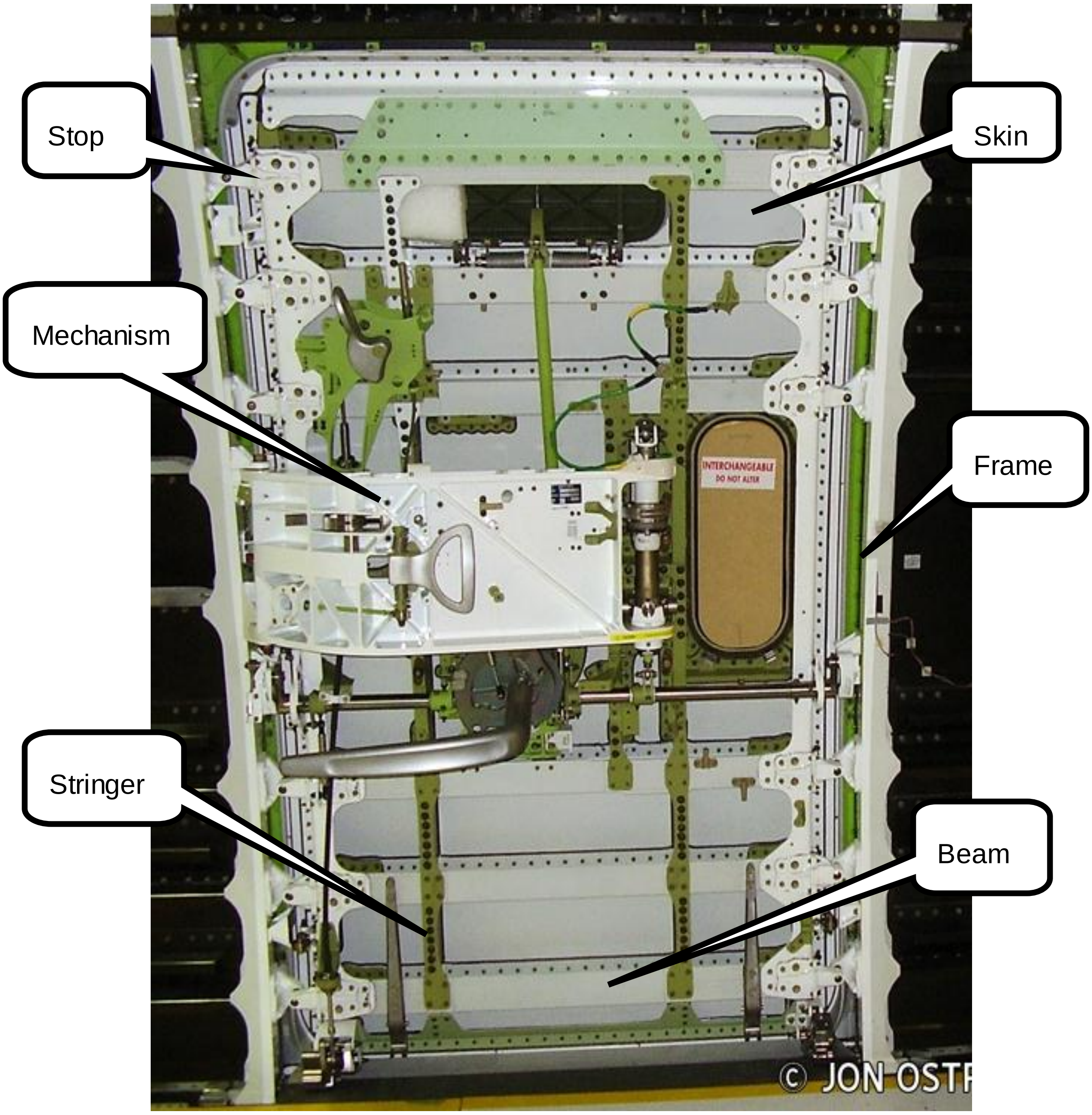


Figure 3-3 Format of the Door Structure [16]

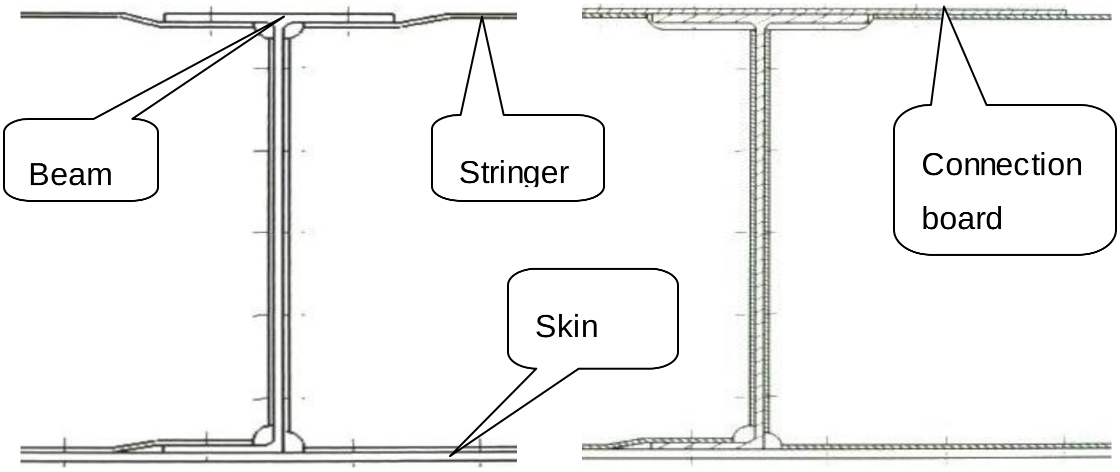


Figure 3-4 Continuity of Stringer

3.3 Applied load

In this study, the 2400m (8000ft) altitude standard cabin pressure load is applied, and the ultimate altitude of aircraft flying is assumed to be12000m (45,000ft) above sea level, and it follows the load criteria recommended in chapter 2.1.2.

The applied load is as follows:

- Working load:

As the pressure in 2400m altitude is 10.92PSI while the pressure in 12000m altitude is 2.75PSI. [17]

So, the cabin pressure: $\Delta P = 8.17PSI = 0.056Mpa$

- Ultimate load:

Compression member and shear ultimate pressure: $2.5\Delta P = 0.14Mpa$

Tension member ultimate load: $3\Delta P = 0.168Mpa$

Fail-safe design load: $1.5\Delta P = 0.084\,Mpa$

During the study, flange buckling of beams under compression load and web buckling of beam under shear load also need to be considered.

4 DOOR STRUCTURE DESIGN WITH METALLIC MATERIAL

In this chapter, the feature of plug-type door structure with aluminium material is studied out by theory calculation, and the best combination of door structure was investigated. Then the entire structure FEM model was constructed for analysis with Nastran. According to the comparing between the theory design and the FEM analysis result, the reasonable method of door structure design and the factors affect the weight of the structure are studied out.

4.1 Theory calculation of metallic door structure

In the theory design stage, the door structure is simplified only into the skin, beams and stringer as illustrated in Chapter 3.1.1, but when considering the carrying load, the stringer is neglected. Ignoring the effect of fuselage configuration, the door is assumed to be flat and have N (3,4,5,6,7,8,9,10,11) beams and n (0,1,2,3,4,5) stringers, The total length of the beam is 1120mm, and its boundary condition can be treated as simply supported. The pressure load act on beams can be equal to the uniform distribution load as Figure 4-1 presents. The skin and outer beam flange are treated as tension members; the inner beam flange is treated as compression member, while the web of the beam is treated as shear member. After investigating the door structure with different number of beams and stringers, the critical elements that affect the structure weight are found out, and a best combination of the door structure for FEM analysis is chosen.

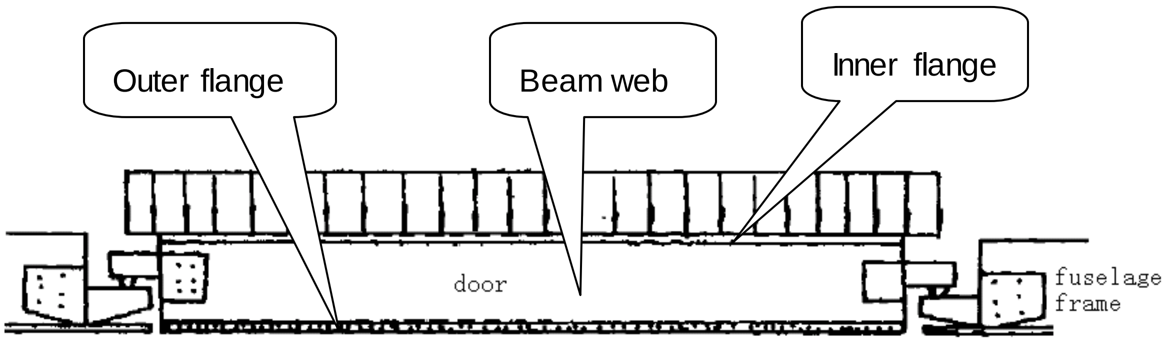


Figure 4-1 Load Sketch of Beam

Generally, the calculation procedure includes 5 steps:

- The calculation of load distribution on beams
- Beam inner flange buckling analysis
- Beam web shear buckling calculation
- Skin thickness calculation
- Beam optimization and weight calculation

And the procedure can be presented in the flow chart as figure 4-2 shows:

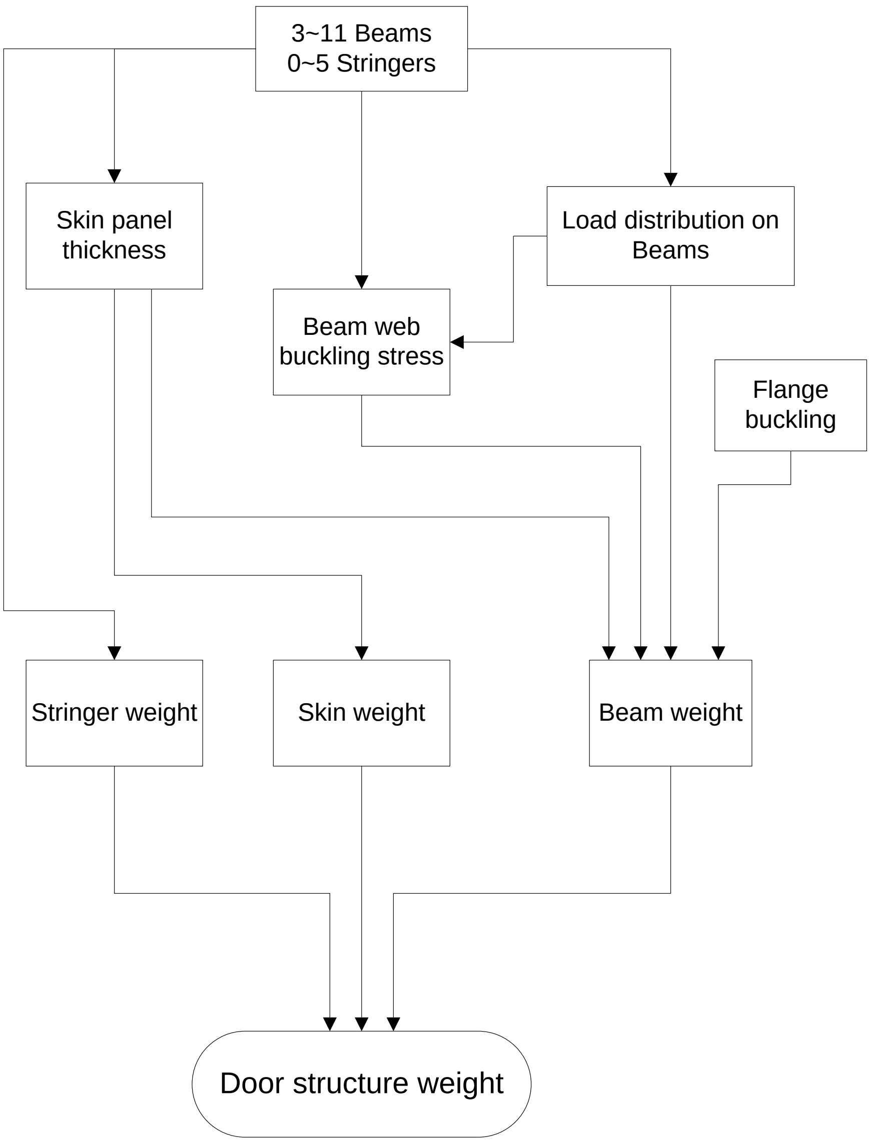


Figure 4-2 Flow Chart of Theory Calculation

4.1.1 The calculation of load distribution on beams

According to the different pressure load on beams as a result of different location, the beams can be generally divided into end beams (B1) which include the upper and lower beam, and middle beams (B2) which are between the end beams, as figure 4-3 shows. And h1 is assumed as below according to different number of beams.

- When N =3, 4, 5, $h1$=220mm
- When N =6, 7, 8, $h1$=200mm
- When N =9, 10, 11, $h1$=180mm

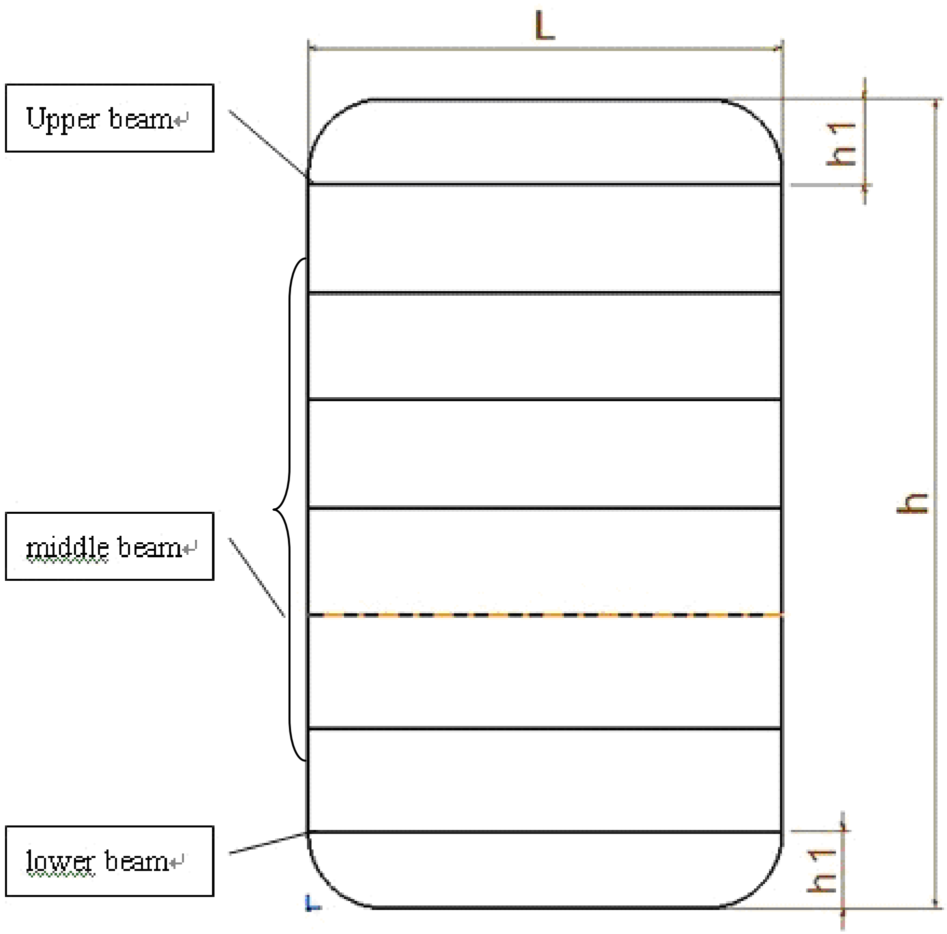


Figure 4-3 Layout of Beams

As the beams are treated as simply supported and uniform distribution type, the load and moment distribution is shown in Figure 4-4.

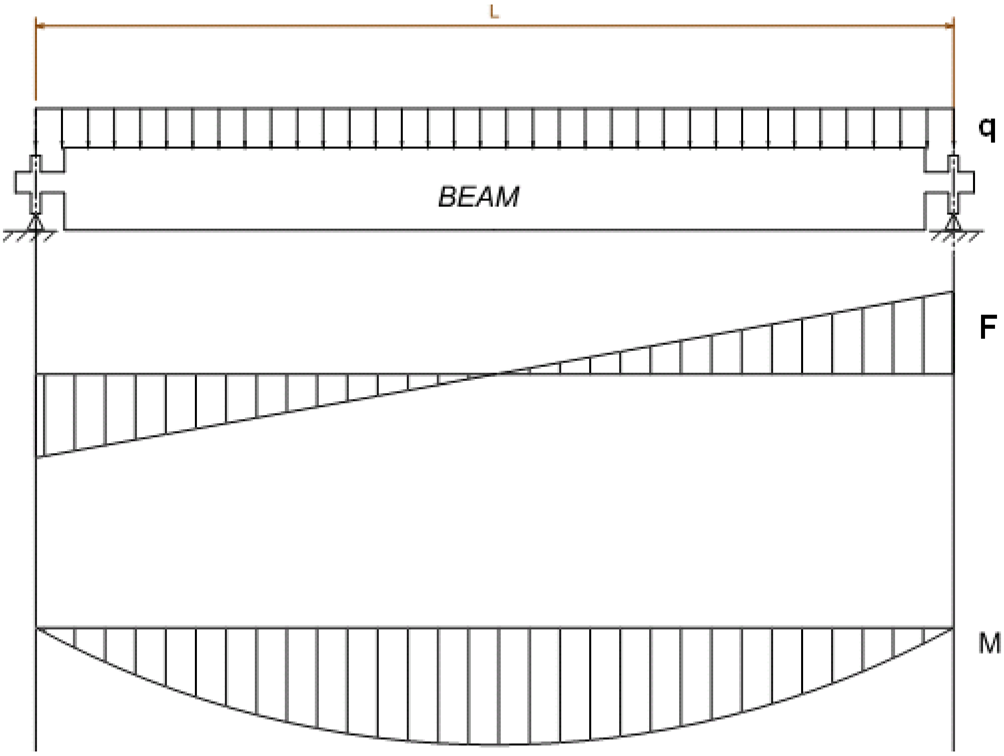


Figure 4-4 Load and Moment Distribution

From the load and moment distribution, the maximum bending load is occurred in the middle of the beam, which can cause the maximum compression and tension stress in the inner flange and outer flange of beam. And the maximum shear load is happened in the tip of the beam which can cause the most serious shear stress. Therefore, the load criteria of the theory design is based on the maximum bending moment and shear load in the middle of beams and tip of beams separately.

From the bending moment Equation 4-1, Equation 4-2 and the detailed calculation procedure in Appendix A.1.1, the ultimate Bending moment and shear load of each beam is presented in table 4-1:

$$M_{\max} = -\frac{qL^2}{8}$$ **Equation 4-1**

$$F_{\max} = F_A = F_B = -\frac{qL}{2}$$ **Equation 4-2**

Table 4-1 Ultimate Bending Moment and Shear Load of Each Beam

	Beam NO.	3	4	5	6	7	8	9	10	11
M_{max} (N.m)		$h1$=220			$h1$=200			$h1$ =180		
	$M(B_{C1})$	12842	10171	8835.7	7683	7134	6742	5680	5439	5247
	$M(B_{T1})$	15410	12205	10603	9230	8561	8091	6816	6527	6296
	$M(B_{C2})$	16025	10683	8012.5	6586	5488	4704	4336	3854	3468
	$M(B_{T2})$	19230	12820	9615	7903	6586	5645	5203	4625	4162
$F_{max}(N)$	$F_{max}(B1)$	45864	36325	31556	27440	25480	24080	20286	19426	18738
	$F_{max}(B2)$	57232	38155	28616	23520	19600	16800	15484	13764	12387

$M(B_{C1})$, $M(B_{T1})$ ——ultimate moment load for compression and tension member of end beam (B1)

$F_{max}(B1)$ ___maximum shear force (N) of end beam

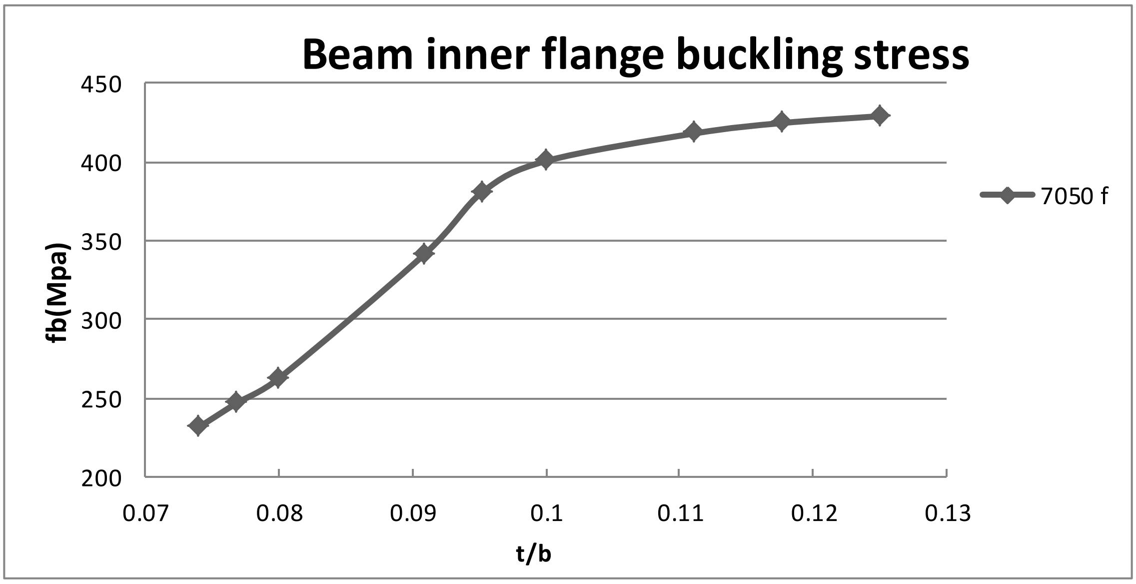
$M(B_{C2})$, $M(B_{T2})$ —— ultimate moment load for compression and tension member of middle beam (B2)

$F_{max}(B2)$ ___maximum shear force (N) of middle beam

4.1.2 The calculation of flange buckling stress

The inner flange of the beam boundary can be treated as one edge free and one simply supported, and the buckling stress is related to the thickness 't' and width 'b' of flange. In this part, it is decided to investigate the relationship of the buckling stress to the thickness and width of flange for beam material 7050-T7451.

According to the detailed calculation process shown in Appendix A.1.2, the beam flange buckling stress f_b against the value $\frac{t}{b}$ is described as follows Graph4-1:



Graph 4-1 Beam Flange Buckling Stress Against $\frac{t}{b}$

- **Conclusion**

➢ As it can be seen from Graph 4-1, when $\frac{t}{b}$≥0.095, the value $\frac{t}{b}$ is nearly linear to the buckling stress and the slope is big, but when $\frac{t}{b}$≥0.095, the buckling stress grows tardiness and keeps over 370Mpa.

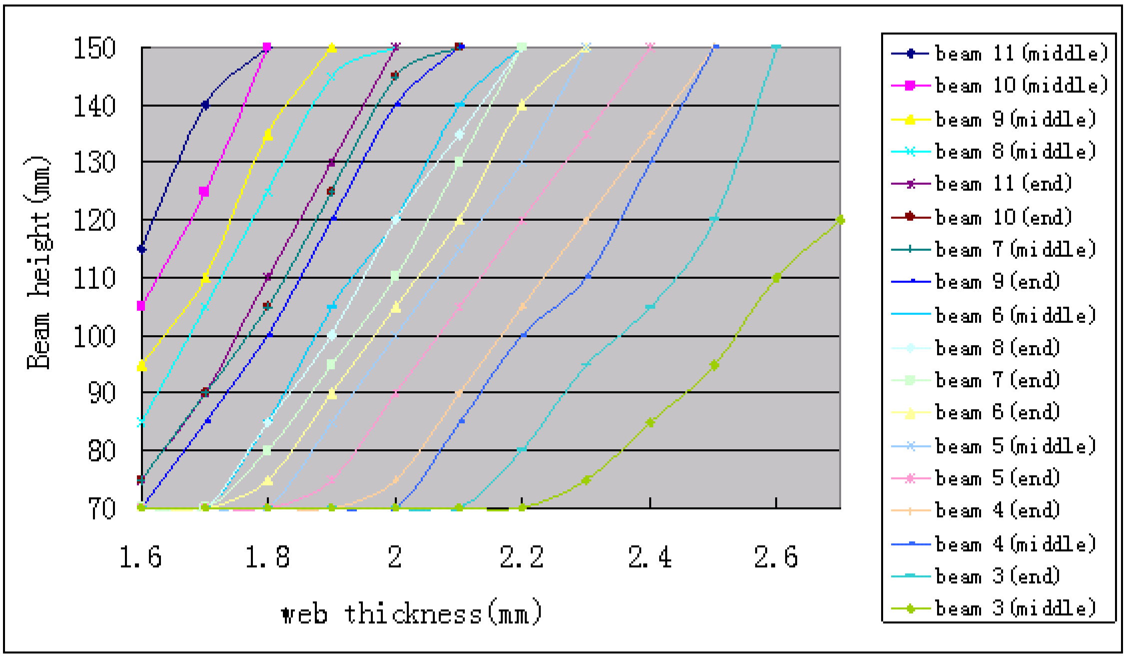
So in order to enhance the ability of resist flange buckling, the rate of the thickness to the width of inner flange $\frac{t}{b}$≥0.095 is applied in beam design.

4.1.3 The calculation of web shear buckling stress

In this chapter, the minimum thickness of the beam web and maximum beam height are studied out according to ESDU 71005[18]. And the detailed calculation process can be seen in Appendix A.1.3. As investigated from existing doors, the height of the beams are normally around 100mm. Actually, when the height is too small, the weight would grows up and it is also not good for deformation performance. While if it is too height, more redundancy of web thickness would be needed to satisfy the shear buckling requirement, then a reasonable range of height (80mm~150mm) was given as the beam height input of the research. And as considering the ability of manufacture, the minimum thickness (1.6mm) of beam web was assumed.

For the structure with 0 stringers, the maximum beam height against minimum web thickness according to web shear buckling stress calculation under 2.5 ΔP is studied out and stated in Graph 4-2.

For the structure with 1\2\3\4\5 stringers, the relationship of maximum beam height against minimum web thickness are stated in Appendix A.1.3 and the feature of them are quite similar.



Graph 4-2 Beam Height against Beam Web Thickness of 0 Stringers

- **Conclusion**

➢ When the web thickness increases, the allowed maximum beam height nearly linear goes up.

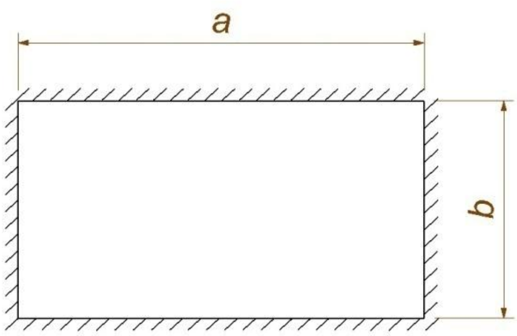
➢ With the same beam height, when the load increases, the beam web needs to be thicker. Or, with the same beam web thickness, when the load increases, the beam height needs to be lower.

From Graph 4-2 it can be seen that, while doing the beam calculation, the value of web thickness to the beam height should below the lines in Graphs to resist the web buckling.

4.1.4 Skin thickness calculation

This part is to calculate the minimum thickness of skin panel for different structure arrangement with the ESDU 71013[19].

For the rectangle panel with pressure load, the total stress is at the centre and the edge and for the maximum total stress on the diagonal where it may be greater.



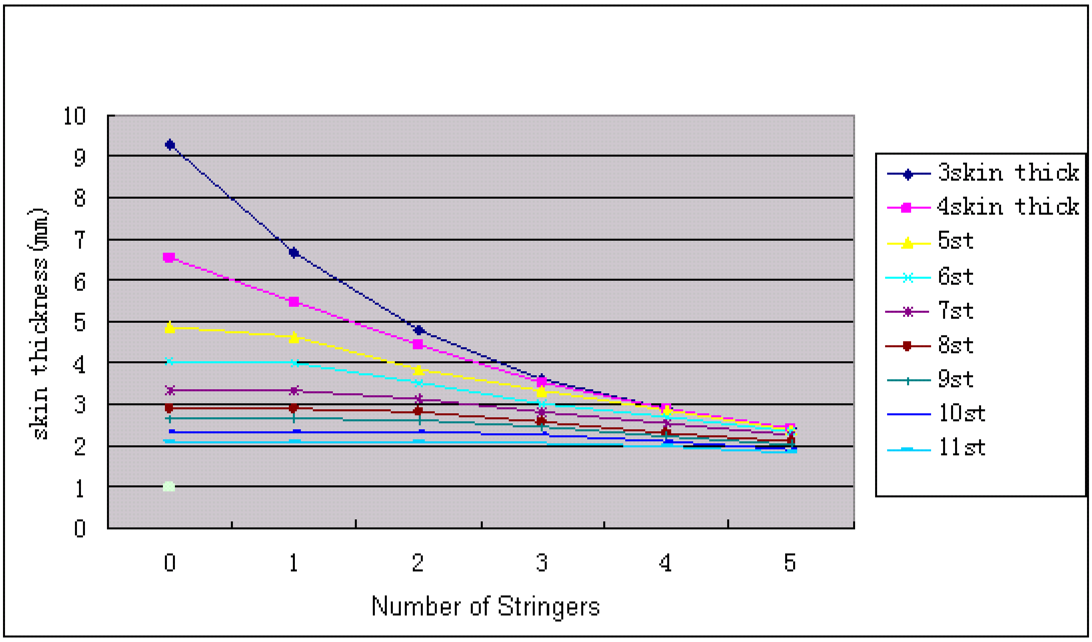
The skin is divided into small piece of panels by beams and stringers, and the maximum panel size for each combination is selected to calculate and the calculation process can be seen in Appendix A.1.4.

Each skin panel boundary constraint can be treated as fixed in rotation and free in translation. The calculation result is stated in Graph4-3 and Graph 4-4 as follows.

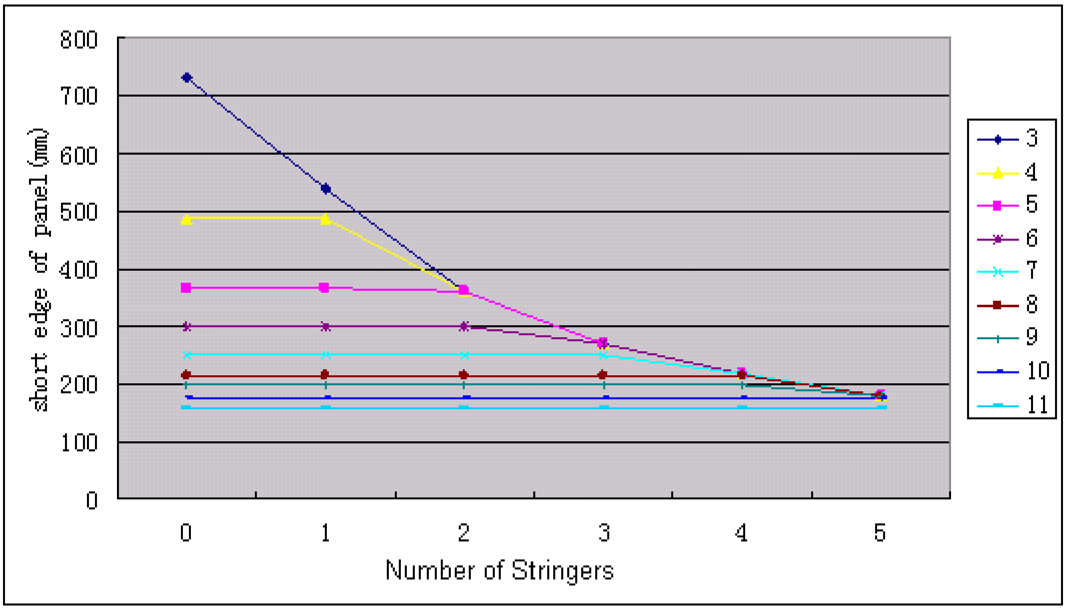
- **Conclusion**

It can be seen from graph 4-3 and graph 4-4.

➢ When the beams arrangement is 8 to 11or the stringer arrangement is 4 to 5, the skin thickness does not change much, and keeps below 3mm. This is because, when the number of the beams or the stringers is bigger, the short edge is usually keeps small. Actually, the rectangular skin thickness under certain load is quite related to the dimension of short edge, the shorter the short edge is, the thinner the skin thickness is. And when the short edge of skin panel is less than 250mm, no matter how many beams and stringers the door has, the skin thickness can below 3mm.



Graph 4-3 Skin Thickness against Number of Beams

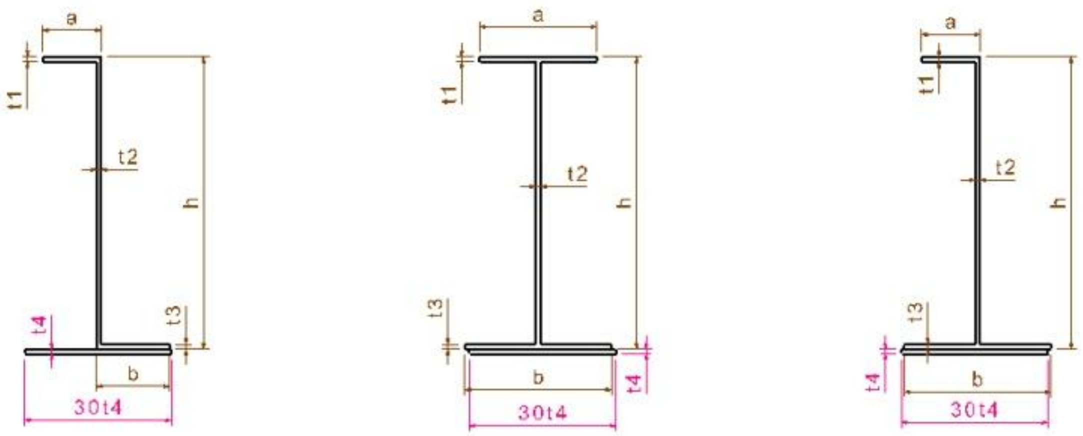


Graph 4-4 Short Edge of Panel against Number of Beams

So, when doing the door structure design, it is important to limit the distance of beams or stringers, and make sure at least one of the distances is no more than 250mm.

4.1.5 Beam calculation

The aim of this section is to investigate the effect to the beam weight of each element according a study case, and then considering of this effect, calculate out the optimised beam cross-section and dimension. The beam cross section and dimension was assumed as follows, and for the second type of the beam, half of “a” was considered as flange width when calculate the buckling stress.



The beam calculation based on the Equation 4-3 to 4-6 as below.

$$I_{xx} = \sum Ay^2 + \sum \frac{bh^3}{12}$$ **Equation 4-3**

$$\bar{y} = \frac{\sum Ay}{\sum A}$$ **Equation 4-4**

$$I_{NA} = I_{xx} - A\bar{y}^2$$ **Equation 4-5**

$$f = \frac{My}{I_{NA}}$$ **Equation 4-6**

In order to study out the effect of each element to the beam weight, a Matlab programme was written as Appendix A.1.5 illustrates.

- **The inputs of the calculation include:**

$M_{\max}, a, b, h, t_1, t_2, t_3, t_4$

$M_{\max}: M(B_C)\ 2.5\Delta p$ For inner flange, $M(B_T)\ 3\Delta p$ for outer flange from table 4-1.

A reasonable range was given for the parameter a, b, h, t_1, t_2, t_3 according to manufacture consideration and investigation of other doors.

t_1 =1.5:0.1:3;

t_2 =1.8:0.2:3.5;

t_3 =1.8:0.2:3.5;

a =20:2:60;

b =22: 2:60;

h =80:5:150

For the skin thickness t_4 , it is follows the result of chapter 4.1.4.

In order to enhance the ability of resist flange buckling, the rate of the thickness to the width of inner flange $\frac{t_2}{a}$ ≥0.095 is applied and $\frac{t_2}{a}$ >0.049 for two side inner beam flange, and the inner flange ultimate stress is applied as 370Mpa.

- **Load criteria:**

For the beam inner flange, the stress is under $2.5\Delta p$. The compression stress should be less than the buckling stress 370Mpa;

For the tension members, the stress of the beam outer flange is less than the 7050-T7451 ultimate stress 524Mpa.

For the shear members, the value of web thickness to the beam height should below the lines in Graphs of shear buckling in chapter 4.1.3 to resist the web buckling.

- Output:

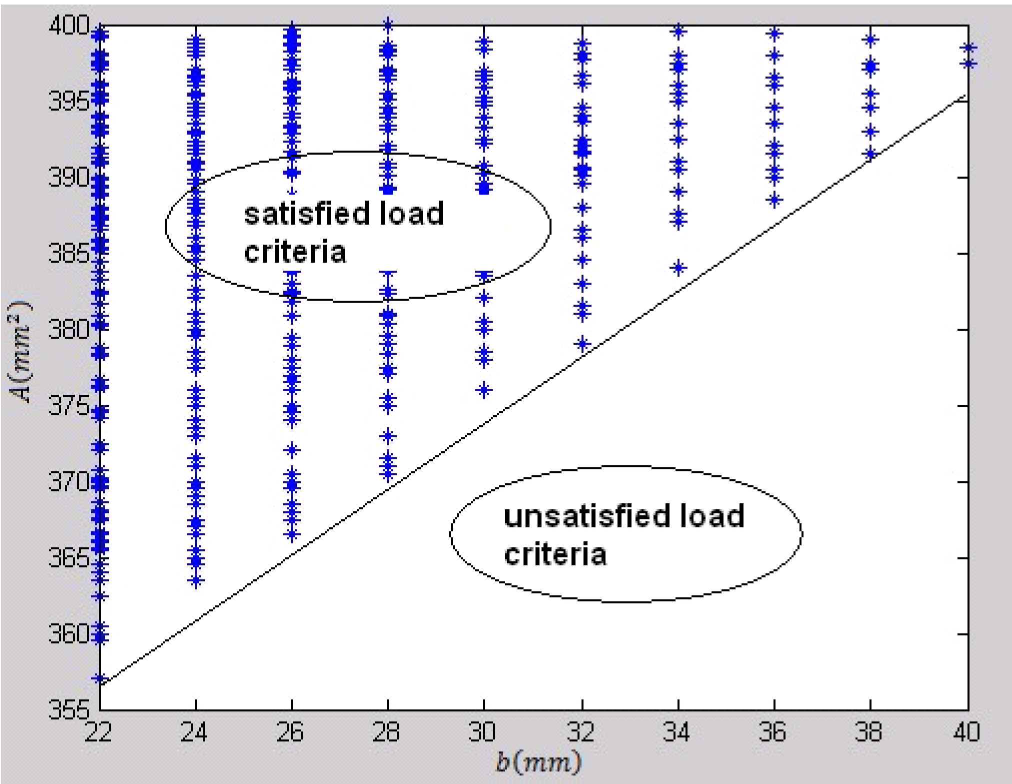
The relationship of the area of beam cross section A with other parameters $a, b, h, t_1, t_2, t_3, t_4$ is put out and investigated.

- Case study

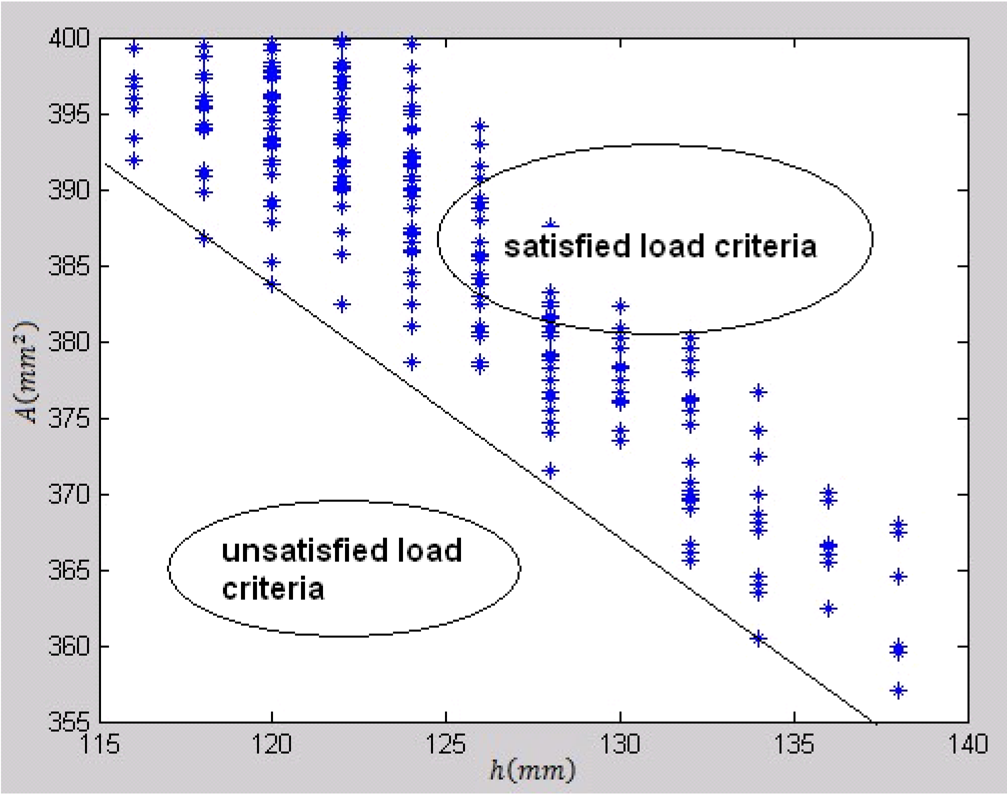
In the case of 6 beam with 2 stringer, the relationship of each dimensions with the beam cross-section area A (which can be treated as equal to the beam weight) shows in the below graphs.

Satisfied load criteria: The area meets the load criteria which include the tensile stress, compression and compression buckling stress, shear and shear buckling stress.

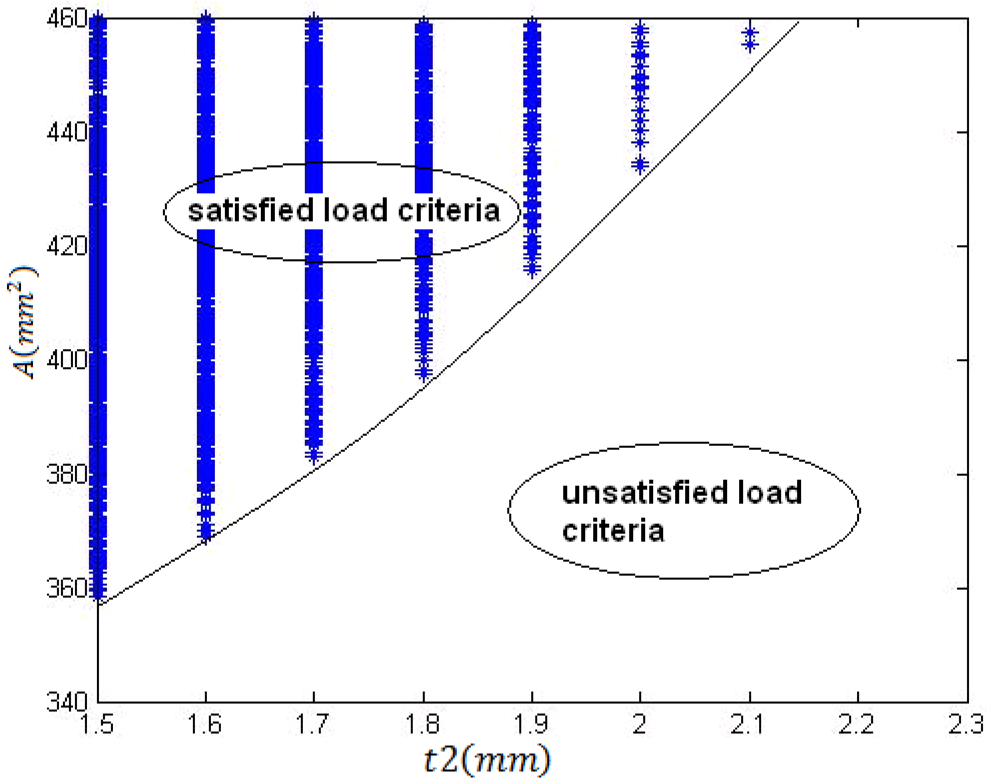
Unsatisfied load criteria: The area doesn't meet the load criteria.



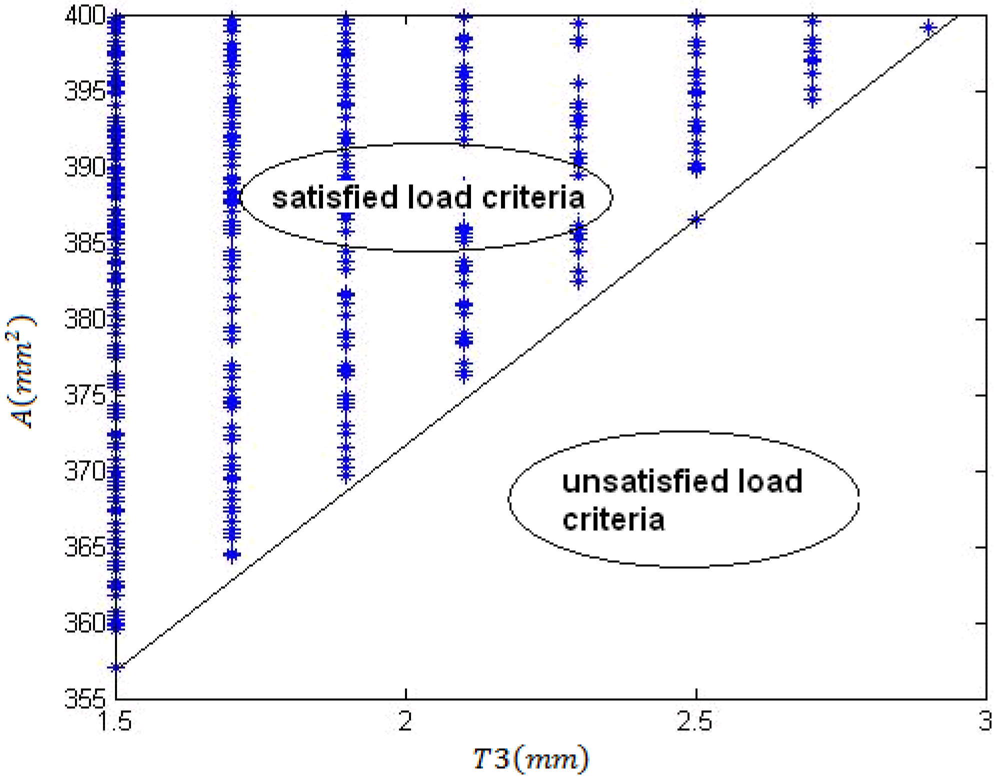
Graph 4-5 Beam Outer Flange Width against Beam Cross-section Area



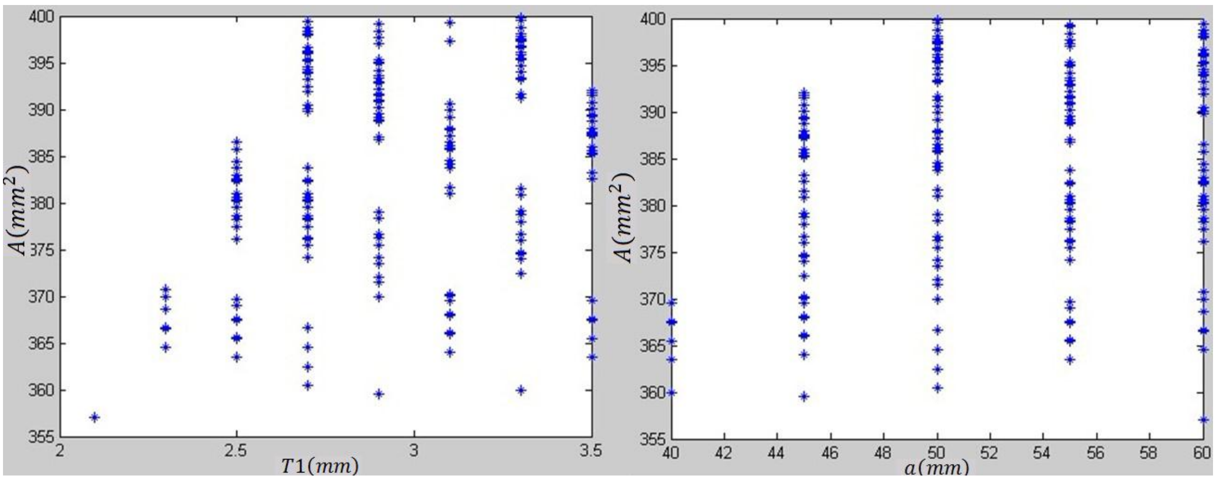
Graph 4-6 Beam Height against Beam Cross-section Area



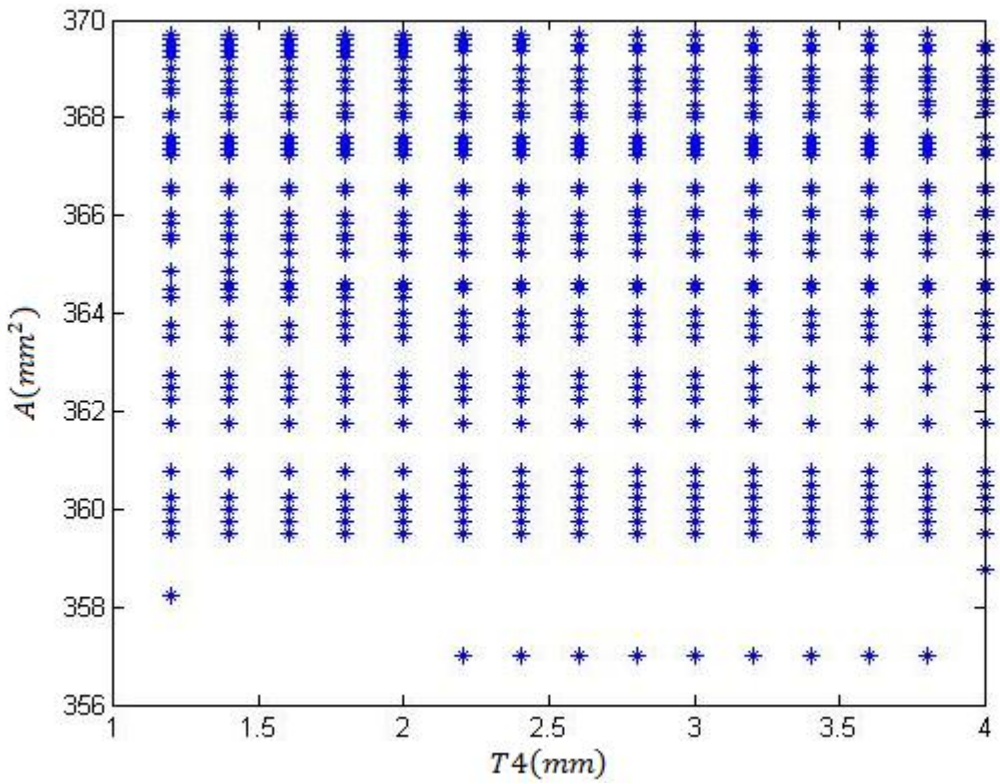
Graph 4-7 Beam Web Thickness against Beam Cross-section Area



Graph 4-8 Beam Outer Flange Thickness against Beam Cross-section Area



Graph 4-9 Thickness and width of the inner flange against the Beam Cross-section Area



Graph 4-10 Skin Thickness against Beam Cross-section Area

- **Conclusion**

➢ From graph4-5, graph4-7 and graph4-8, it can be seen that the width of beam outer flange' b', the web thickness 't_2', the outer flange thickness 't_3' have negative effects on weight reduction. When they increase, the weight of the beam goes up.

➢ From graph4-6, the height of beam 'h' has positive effect on minimizing the beam weight. When it becomes higher, the weight of the beam becomes lower.

➢ The effect of skin thicknesses 't_4', and the thickness 't_1' and width 'a' of beam inner flange to beam weight are not apparent.

So In order to reduce the beam weight, the 'b', 't_2', 't_3' parameters are all assembled in the minimum side, 'h' are in the maximum side. Before further calculation, the minimum value of 'b', 't_3' are assumed as below, because of the manufacture ability consideration.

Outer flange: $b \geq 22mm$, $t_3 \geq 1.8mm$

According to the Appendix A.1.5 programme, calculating the minimum weight of each beam for each combination, the result is shown in the Appendix A.1.5.

4.1.6 Result and conclusion

According to the calculation of beam for each combination, the minimum weight of the beams and structure total weight was calculated. And the detailed process is in the Appendix A.1.6.

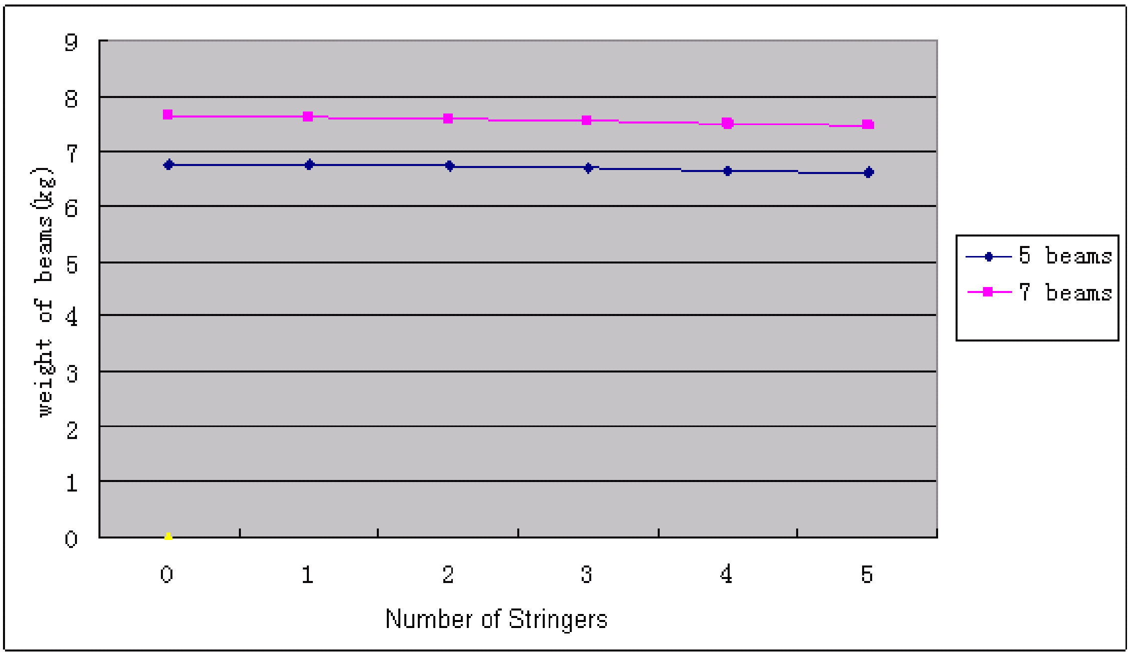
Below are the results and conclusions.

Weight of beams

The total minimum weight of beams for the 5 and 7 beams structure format is calculated, as shown in Graph 4-11 and Table A-3. It can be seen that the beams weight doesn't changes much when the stringer NO verifies. Then, for structures with other numbers of beams only the weight of beams with 2 stringers were calculated, which is treated as stand for the average minimum weight of the beam. And the beams weight for other number of beams is stated in Graph 4-13.

Conclusion

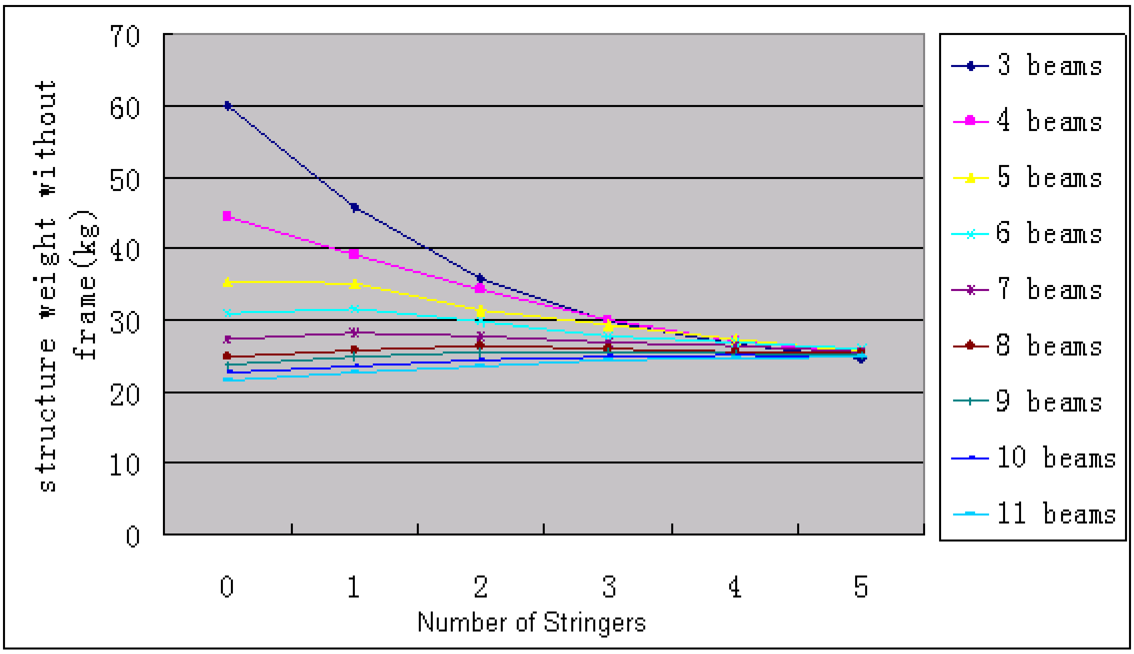
- From the result of beam calculation, it can be know that the numbers of stringers has little effect to the beam weight, which also means the thickness of the skin has little effect on the Beam minimum weight.
- The beams weight can gently increase while the beams number increases.



Graph 4-11 Effect of Stringer Number on Beam Weight

The total weight of the door structure (without frame)

In this part, when it refers to the total weight of the structure, only the weight of beams, stringers and skin are considered, and the door frame is considered similar for each combination, as table A-5 and Graph 4-12 shows.

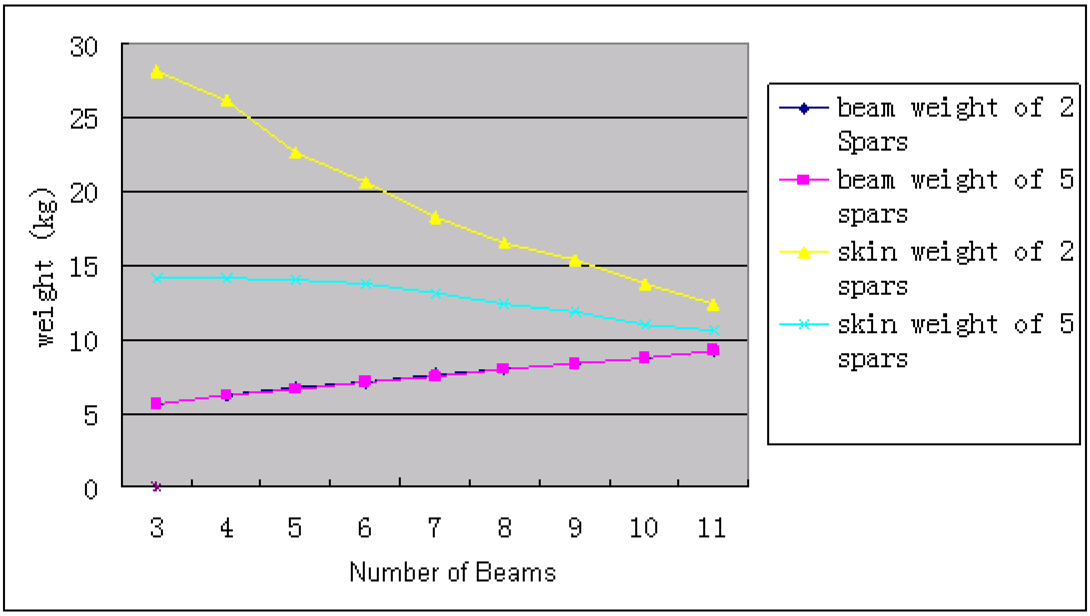


Graph 4-12 Total Weight of Structure (without Door Frame)

- From Graph 4-12 it can be seen, when beams numbers exceed 7 or stringer numbers exceed 4, the structure weights can keep in a range. And when comparing with Graph 4-3, it can be noticed that in this condition the thickness of skin is always below 3mm. As it has been concluded in Chapter 4.1.4, it also means the width of skin panel divided by beams and stringers is less than 250mm.

The weight contribution to the door structure

The Graph 4-13 shows the weight contribution to the door structure in case of 2 and 5 stringers.



Graph 4-13 Weight Contribution to Structure in Case of 2 and 5 Stringers

- From graph 4-13, it can be concluded that the skin contribute much greater than beams to structure weight, especially when the beams and the stringers numbers are fewer.

4.1.7 Door structure model

In this part, the door structure is constructed according to the result of theory calculation, and additionally, the door frame is added.

Firstly, a best combination of beams and stringers is selected. According to the theory calculation, it can be easily seen that the weight of the door structure doesn't change much when the beams numbers exceed 7 or stringer numbers exceed 4. So if just considering the weight of the structure, many combinations can be chosen. However, in this thesis, for considering of the manufacture ability and the fail-safe requirement, the door structure with 7 beams and 4 stringers is selected to study.

- **Manufacture consideration**

From the beam web buckling analysis, it can be known that when the beams number is bigger, the web thickness is thinner, which can be less than 1.7mm. Actually it is difficult for machining as the beam height is normally higher and the real beam geometry is usually complicated.

And another problem for more numbers of beams and stringers is that it would cause more time and cost assumption for producing and assembling more parts.

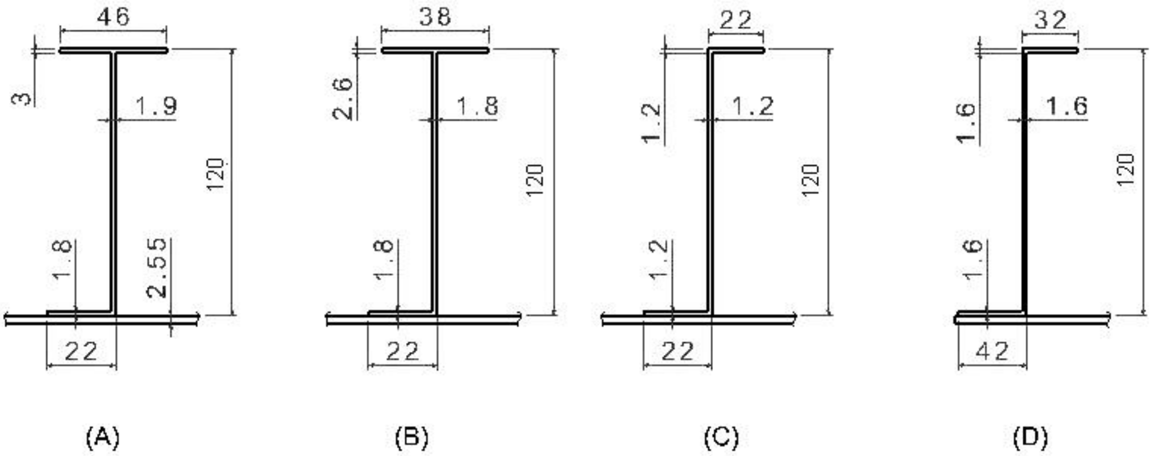
So, when considering of manufacture, it would be much better while applied fewer beams and stringers.

- **Fail-safe requirement consideration**

As specified in design criteria, the door structure should be design to satisfy the one stop failed requirement. Hence, the beams number should not too fewer, otherwise the structure or the next stop would be hard to withstand the concentrate load when one stop fails.

According to investigate, the same type doors of other aircraft; they usually have 7 beams. As a result, the door structure with 7 beams and 4 stringers was selected to study. The beams and assumed stringer and frame dimension are shown as below and the 3D CATIA model shows in Figure 4-5.

The weight of the CATIA structure mode and the percentage for each member contributes to the total weight is presented in Table 4-2.



(A)The skin thickness and the end beams dimension;

(B)The 5 middle beams dimension;

(C)The 4 stringers dimension;

(D) The frame dimension

Table 4-2 Weight of the CATIA Structure Model

component	skin	end beam	middle beam	stringer	frame	total
Weight(kg)	15	2.35	5.1	3.82	4.76	31.3
Percentage (%)	48	7.6	16.4	12.3	15.4	

From table 4-2, it can be seen, the skin contributes nearly half weight to the structure.

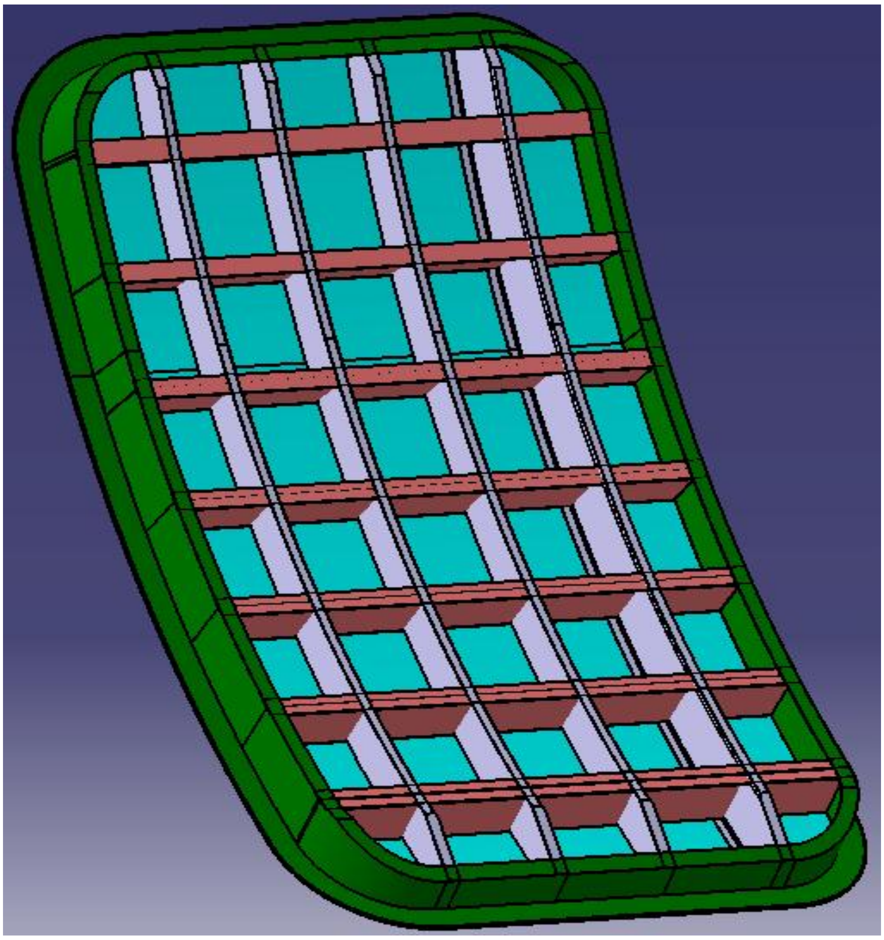


Figure 4-5 3D CATIA Model of the Door structure

4.2 FEM analysis of metallic door structure

When it mentions to FEM calculation accuracy, 3D solid model is usually used for thick solid members while 2D shell element is usually applied for thin members, therefore, for the skin and beam web are modeled to be 2D shell elements. As there are some difficulties for modeling the beam flange in 2D models, the flange of beams is applied 1D bar element. The element size is 20 ×20mm, figure 4-6 shows the finite mesh of the door structure.[20]

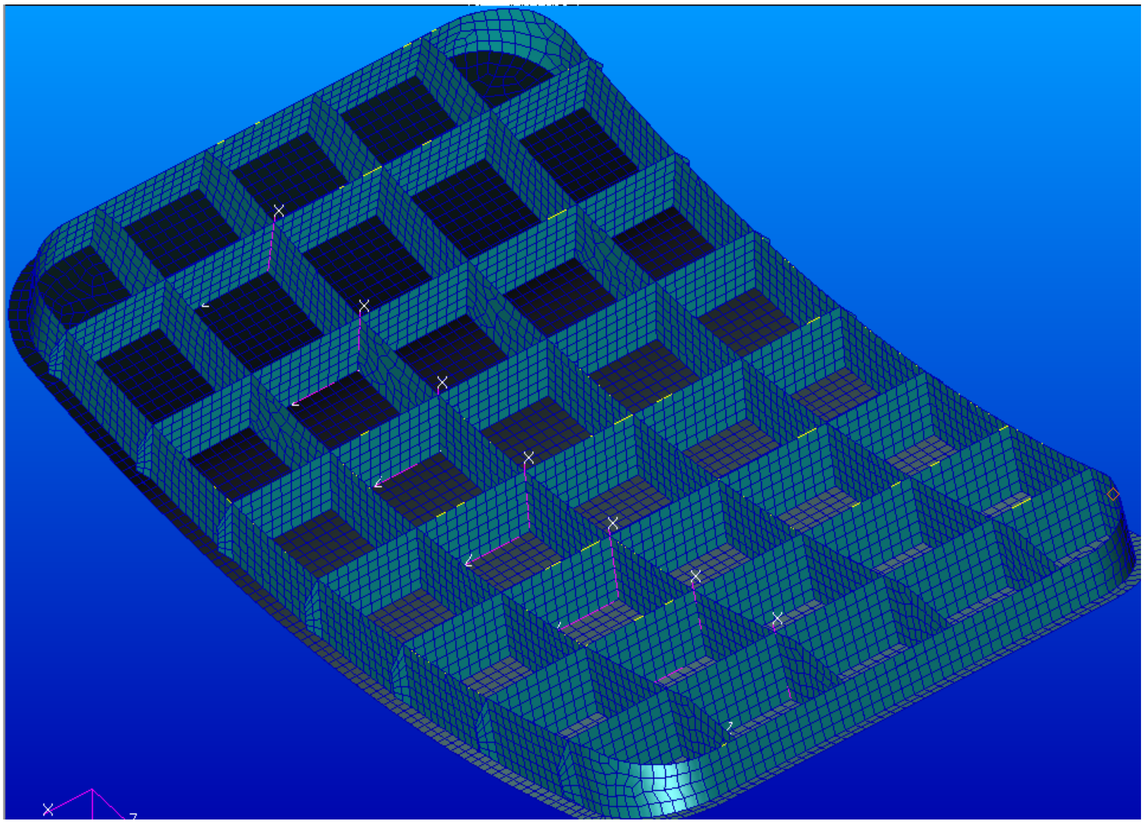


Figure 4-6 Finite Mesh of the Door Structure

4.2.1 Boundary constraint

14 stop elements are applied to transfer constraint in radial direction, which is simulate to 14 stops at each end of the beam against the fuselage structure. When calculate the fail-safe cases, one stop constraint of each beam is removed gradually.

2 nodes in the middle of the skin are constraint in other 2 transfer directions.

The pressure is applied on the all the skin panel.

The constraint, the definition of radial direction coordinate system and the applied pressure load can be seen in Figure 4-7.

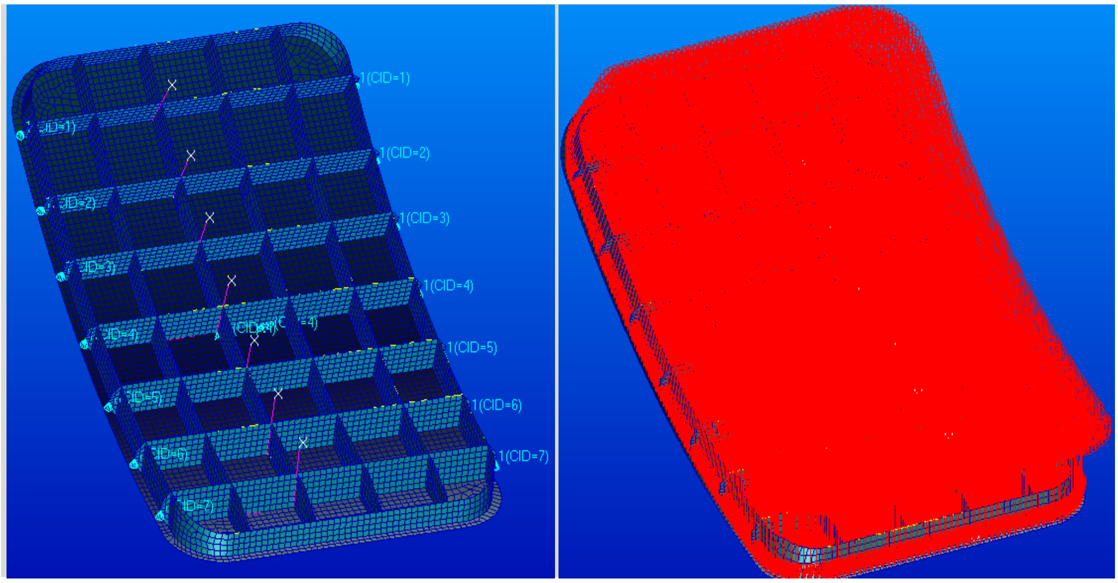


Figure 4-7 Constraint and Pressure Load

4.2.2 Result comparison with theory calculation

All of the analysis in this part is based on the LINEAR solution type.

- **The tension、compression、shear member**

According to FEM analysis, it can be seen that the maximum tension stress is in the edge of the skin panel, while the maximum compression stress is in the middle of the inner beam flange and the maximum shear stress is in the end of each beam, which is quite the same as chosen for theory calculation. The ultimate stress comparing with FEM analysis and theory calculation is shown in Table 4-3.

Table 4-3 Stresses Comparison of FEM Analysis and Theory Calculation

Pressure load	member		theory stress（Mpa）	FEM stress（Mpa）
$3\Delta P$	tension member		466	387
$2.5\Delta P$	compression member		370	281
$2.5\Delta P$	shear member	end beam	122	130
$2.5\Delta P$		middle beam	99	116

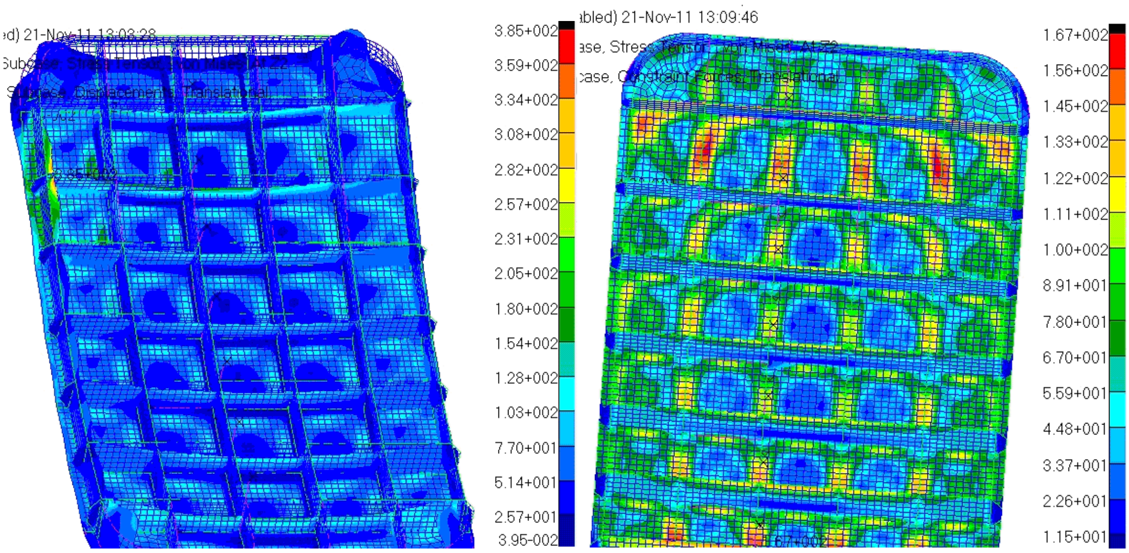
It can be seen from the table, the theory stress is a little higher than FEM results for the tension and compression members, this should be because the door is simplified into only beams during calculation, but actually the frame and stringers do have some effects on the door structure which cause the tension and compression stress reduces during FEM model analysis.

- **The stop failed**

The fail-safe case is divided into 4 groups, as the door structure is symmetric from left to right, upper to lower. So, the first and last beam stop has the same failure results, while the second is the same as the sixth, the third is the same as the fifth. The analysis result of these failure cases is listed in Table 4-4 and shown in Figure 4-8:

Table 4-4 Result of Different Stop Failures

Pressure load	Beam NO.	von mises (Mpa)	max principal (Mpa)	max shear (Mpa)
$1.5\Delta P$	1/7	382	377	197
	2/6	167	158	87.6
	3/5	167	158	87.5
	4	167	158	87.3



Beam 1/7 beam 2~6(similar)

Figure 4-8 Von Mises Stress

It can be seen from the result that the failure situation is much more serious when the stop of end beam fails. And for other stops of middle beam failed, the stress is quite similar.

When one of the end stop failed, the stress was then concentrated in the next stop area and the stress is much higher than other area, the maximum stress occurs in the frame flange, as figure 4-8 shows, and it reversed to tensile stress.

From the table 4-4 it can be know that the door structure is fulfilling the one stop fail criteria.

As considering the stress concentration, it also can conclude that the beams number is hard to reduce.

- **The load force reaction**

The load reaction on constraint under $3\Delta P$ and under $1.5\Delta P$ while one stop fails is calculated and analyzed, as table 4-5 and table 4-6 shows.

It can be seen the load reaction of theory calculation and FEM analysis are quite similar despite a slight difference exist, which should be for the effect of the configuration as when calculating in theory the door is only assumed as flat.

The force load concentration is much higher when the end stop fails than the middle stop, and the force is also higher than the normal situation under $3\Delta P$

Table 4-5 Beam Stop Reaction Force under $3\Delta P$

	Beam stop reaction force		
	Total load F(N)	End beam stop reaction load F1(N)	Middle beam stop reaction load F1(N)
theory	344400	31721.05	22657.89
FEM	358774	34003.6	24230.57

Table 4-6 Beam Stop Reaction Force When One Stop fails under $1.5\Delta P$

member	max stop reaction force (N)
end beam stop	40,566
middle beam stop	20,222

- **The stress and displacement under working load**

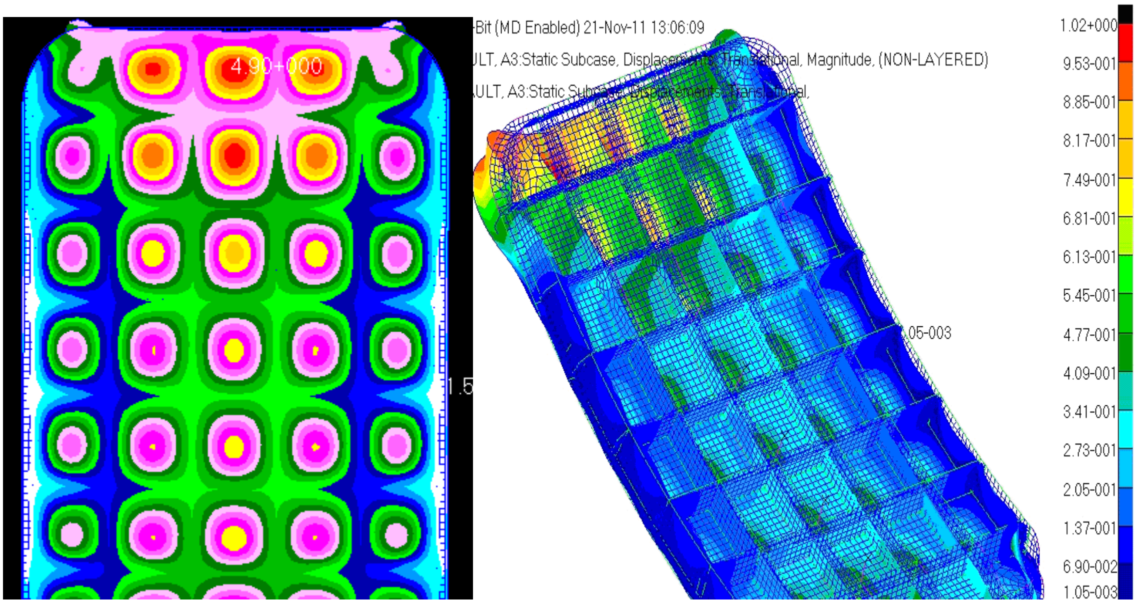
According to the analysis of the door structure under working load, it can be seen from table 4-7 and table 4-8 that the stress is far below the allowable stress. The max displacement of normal situation on the sealing area is 3.2mm, and it is 6.5mm while end beam stop fails and happens in the corner.

Table 4-7 Stresses Comparison under Working Load

Pressure load	member		theory stress（Mpa）	FEM stress（Mpa）	Displacement(mm)	
					Sealing area	Max displacement
ΔP	tension member		155	130	3.2	4.9
	compression member		123	94		
	shear member	end beam	41	43		
		middle beam	35	40		

Table 4-8 Maximum Stress and Displacement under Wording Load when One Stop Failed.

Pressure load	Beam NO.	von mises (Mpa)	max principal (Mpa)	max shear (Mpa)	Displacement (mm)
ΔP	1/7	255	250	131	6.5
	2/6	111	103	63	4.8
	3/5	111	103	63	4.8
	4	111	103	63	4.8



Normal **one stop failed**

Figure 4-9 Displacement under Working Load

4.3 Conclusion

The aluminium structure of Type A door is investigated in this chapter both by theory calculation and FEM analysis. From the comparing of theory calculation and FEM analysis, it can be concluded that the theory design method is reasonable, and it can be followed as a standard way of plug type door structure primary design as the Figure 4-2 shows. After theory calculation, the structure and fail-safe case can be analysed by FEA.

Some features of door structure design have been studied out according to the theory calculation which can be listed as follows:

The weight of a Type A door structure (without frame) can keeps below 30kg and doesn’t change much when beams numbers exceed 7 or stringer numbers exceed 4, which also means when the skin thickness less than 3mm. And the skin contributes greater weight to the structure than beams, especially when the beams and the stringers numbers are fewer. For the Type A door with 7 beams and 4 stringers, the weight percentage of skin to door structure can be nearly a half.

As the skin thickness is relate to the short edge width of skin panel divided by beams and stringers to a great extend, the maximum distance of beams or stringers should be less than 250mm so that the skin thickness can keeps below 3mm.

Beam is another contributor to the door structure weight and it would contribute about 25% to the total structure weight. The elements which can affect the weight of beam are studied out in Chapter 4.1.5. The width of beam outer flange' b', the web thickness 't_2', and the outer flange thickness 't_3' have negative effect on weight reduction while the height of beam 'h' has positive effect on minimize beam weight. The effect of skin thickness 't4' and the thickness 't1' and width of bean inner flange to the beam weight is not apparent.

From FEM analysis of fail-safe case, it can be known that the failure situation is much more serious while the stop of end beam failed. As the force concentration of end stop failed is higher than in normal condition under $3\Delta P$, and the displacement of the corner area is large. It can be conclude that the number of beams can't be minimised.

5 DOOR STRUCTURE DESIGN WITH COMPOSITE MATERIAL

In this chapter, the door structure designed with composite material is investigated with both the theory calculation and FEM analysis, the procedure follows the way of the metallic door designed.

5.1 Theory calculation of composite door structure

In the theory calculation stage, like the metallic door, first 3~11beams and 0~5 stringers are assumed as the structure format, and then according to the calculation of the load distribution, the beam flange buckling stress, beam web shear buckling stress, skin thickness analysis, and the beam analysis, work out the best composite structure. Actually, the load distribution has been calculated in Table 4-1.

5.1.1 Applied composite material

High strength Carbon/Epoxy unidirectional prepreg is applied for all members of the composite door structure, including the skin, the beams, the stringers and the frame.

Since the load is not the same for different components, like the main load for the skin and the beam outer flange is tensile stress, the main load for the beam web is shear stress, and for the beam inner flange is compressive stress so that the layout applied for these parts are also different. Therefore, considering the main load for each component takes, the skin applied the quasi-isotropic lay-up which means in each of the four directions the laminate numbers of the fibres are equal. The beam flange applied the Max.Rec. 0° lay-up which means can arrange the maximum of 50% fibres in 0° direction, and for the beam web the Max.Rec. ±45° of maximum of 76% fibres in ±45° direction was applied.

Actually, as considering the thickness of laminate, the percentage of the fibres in each direction is slightly modified as Table 5-1 shows

Table 5-1 Laminate layup for each components

component	Remark	Layup (plies %)		
		0°	±45°	90°
Skin	Quasi-isotropic	25	50	25
Beam web	Max.Rec.±45°	12.5	75	12.5
Beam flange	Max.Rec.0°	50	37.5	12.5
Stringer/ frame web	Max.Rec.±45°	12.5	75	12.5
Stringer/ frame flange	Max.Rec.0°	50	37.5	12.5

The lay-up and thickness for each composite is illustrated in Appendix A.2.1 and the properties are calculated by COALA [21].

- **Laminate strain**

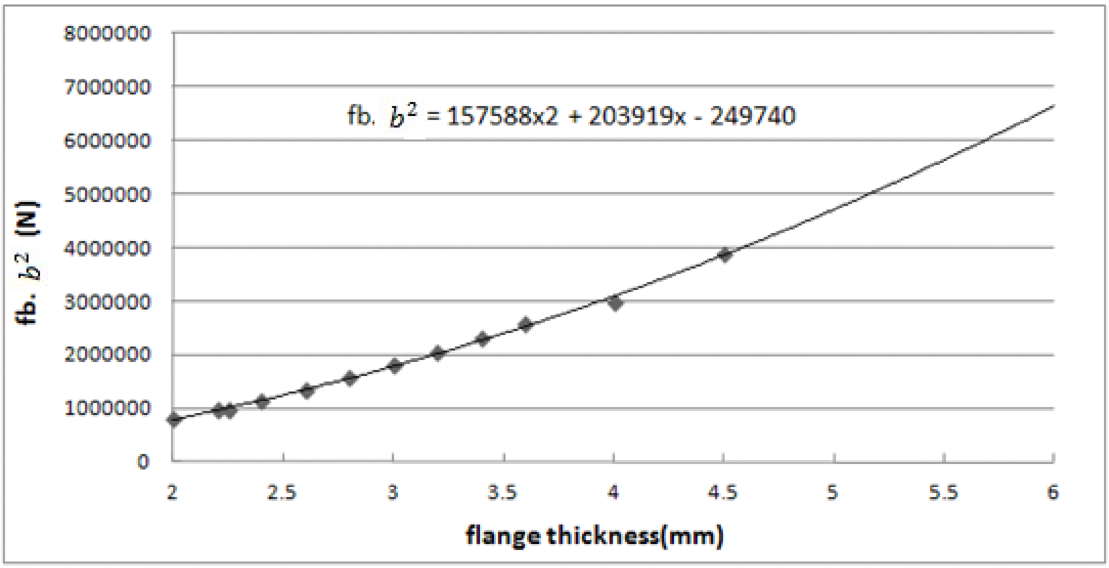
As considering the damage tolerance of the structure, the laminate strain normally is restrained in a reasonable range, and it can be calculated by equation 5-1. In this thesis, for simple concerned, a laminate strain to $4000\mu\varepsilon$ micro strains is assumed. Actually, according to calculation, the applied laminate strain is all below this criteria, the result is as table A-9 shows.

$$\varepsilon = f / E$$ **Equation 5-1**

5.1.2 The calculation of flange buckling stress

The beam flange buckling stress is calculated according to ESDU 80023. The ESDU 80023 "gives the elastic buckling loads of thin flat rectangular homogeneous specially orthotropic plates in which the through-the-thickness shear deformations have negligible effect on the buckling loads. The curves are based upon an elastic small deflections theory in which the plate is assumed to be made of a homogeneous orthotropic material whose principal axes of orthotropic are aligned with the edges of the plate (axes, x, y)."[22]

The beam inner flange can be treated as Long plates subjected to biaxial load, sides simply-supported (C=2.0)[21], as shown in Appendix A.2.2, and the relationship of flange width, flange thickness and buckling stress is then studied out and presented in Graph 5-1.



Graph 5-1 Flange Buckling Curve

And the buckling stress can be fitted as the equation 5-2:

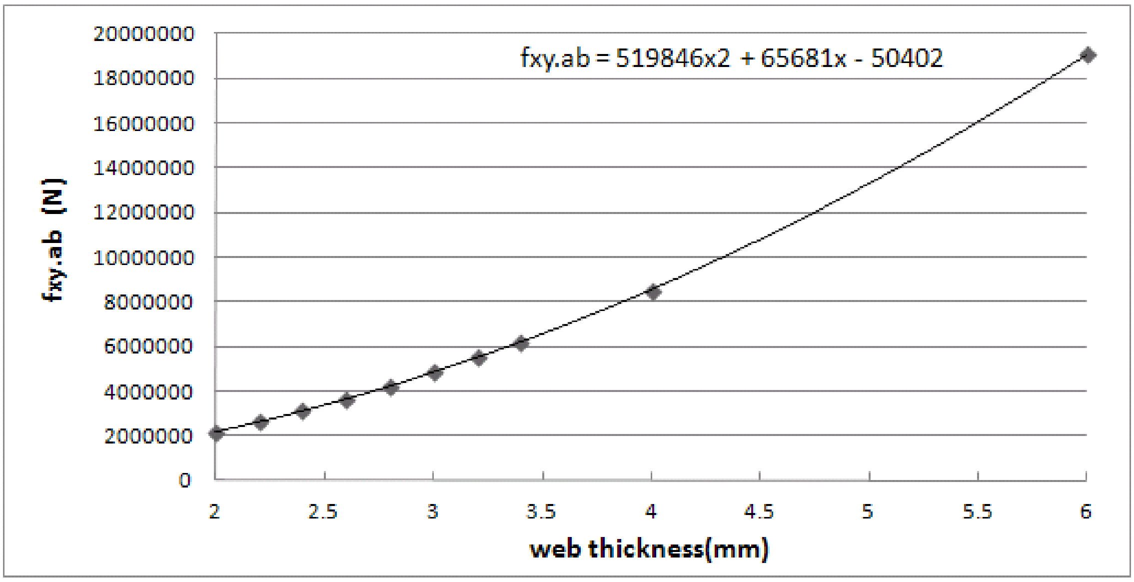
$$f_b = \frac{157588t^2 + 203919t - 249740}{b^2}$$ **Equation 5-2**

5.1.3 The calculation of web shear buckling stress

The web shear buckling stress is calculated out according to ESDU 80023. The details can be seen in Appendix A.2.3. And the relationship of beam height, web thickness and shear buckling stress is studied out and presented in Table A-11 and Graph 5-2.

The web shear buckling stress can be fitted as the equation 5-3:

$$f_{xy} = \frac{519846t^2 + 65681t - 50402}{ab}$$ **Equation 5-3**



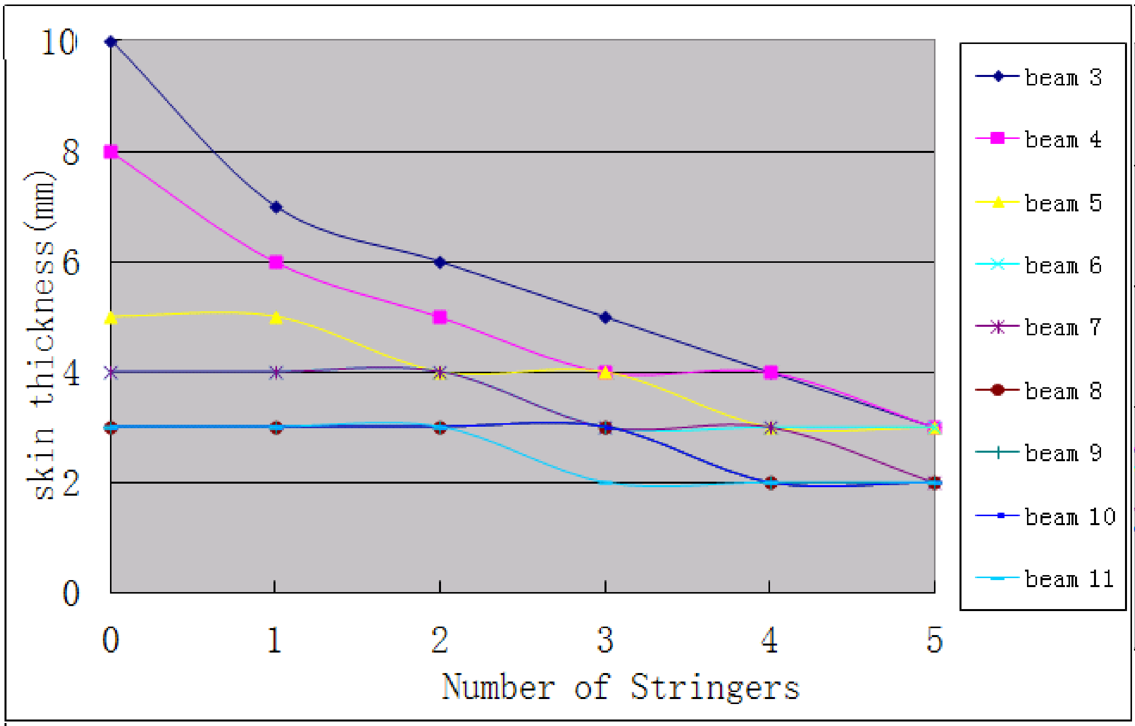
Graph 5-2 Web Shear Buckling Curve

5.1.4 Skin thickness calculation

The skin thickness is calculated according to FEM according to the biggest panel divided by beams and stringers. It uses the 2D shell element, the mesh size is 20×20mm, as mentioned in Chapter 4.1.4, the boundary constraint of each skin panel is treated as fixed in rotation and free in translation, which can be equal to the constraint of the FEM model as:

- The fix rotation in 'X','Y','Z'<0,0,0> and fixed translation in 'Z' direction < , ,0> for the four edges;
- The fixed rotation in 'Z'<,,0> direction and fixed translation in 'X','Y' direction<0,0,>;
- As the skin is treated as tension member, so the $3\Delta p$ pressure load is applied on the skin panel.

The skin thickness is calculated out as table A-13 presented in detail, and also it can be seen from Graph 5-3.



Graph 5-3 Skin Thickness of Composite Door

As it can be seen from Graph 5-3, the trend of the skin thickness curves is quite similar to the aluminium door. When the stringer number is more than 4 or the beam number is more than 6, the skin thickness can keeps below 4mm.

As the composite material changes only can in 1mm grade, for different combination, the skin thickness can be applied the same thickness, but the displacement may be different.

5.1.5 Beam calculation

The procedure of composite door beam calculation is quite similar to the metallic door, although there is some difference.

- The inputs of the calculation include:

$$M_{\max}, a, b, h, t_1, t_2, t_3, t_4$$

$M_{\max}: M(B_C)\ 2.5\Delta p$ For inner flange, $M(B_T)\ 3\Delta p$ for outer flange from table 4-1.

A reasonable range is given for the parameters a, b, h, t_1, t_2, t_3 according to manufacture consideration and investigation of other doors.

t1= [2.25, 4, 4.5, 6.25];

t2=2:2:6;

t3= [2.25, 4, 4.5, 6.25];

a=20:2:60;

b=22: 2:60;

h=80:5:130;

n=0:1:5;

For the skin thickness t_4 , it follows the result of Chapter 5.1.4.

'n' is the number of stringer which is used to calculate the length of beam web panel. And the length can be presented as $l = \frac{1080}{(n+1)}$.

- Load condition and criteria:

- For the beam inner flange

As the flange buckling stress can be calculated by:

$$f_b = \frac{157588 t_1^2 + 203919 t_1 - 249740}{a^2}$$ **Equation 5-4**

The inner flange compression stress under $2.5\Delta p$ should be both less than the buckling stress f_x and Max.Rex.0 ultimate compression stress 700MPa;

- For the tension members, the beam outer flange should be less than the Max.Rex.0 ultimate compression stress 740MPa;

- For the shear members

The applied stress:

$$f_{xy}' = \frac{F_{max}}{t_2 \times h}$$ **Equation 5-5**

As the web shear buckling stress can be calculated by:

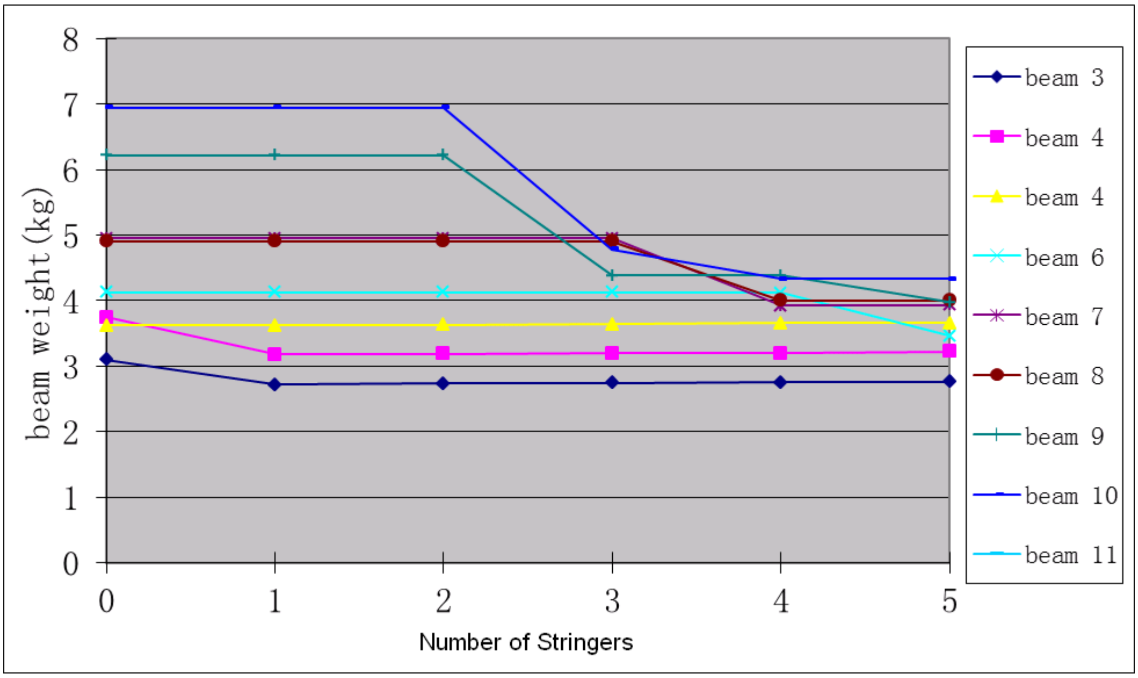
$$f_{xy} = \frac{519846 t_2^{\ 2} + 65681 t_2 - 50402}{\frac{1080}{(n+1)} \times h}$$ **Equation 5-6**

So the condition for beam web is：

$f_{xy}' \leq f_{xy}$ and $f_{xy}' \leq$ 315MPa

- Output:

The minimum area of beam cross-section for each combination and the values of ‘ a, b, h, t_1, t_2, t_3 ’ and the minimum beam weight for each combination, as Graph 5-4 shows.



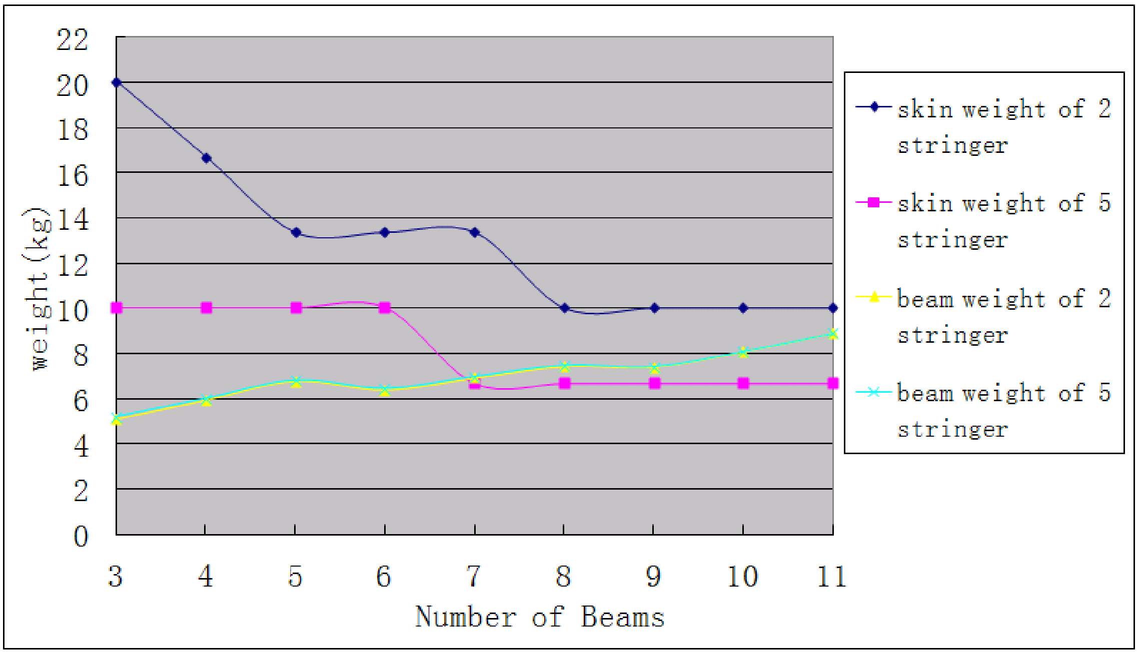
Graph 5-4 Weight of Beams

From Graph 5-4 it can be seen that the weight of beam keeps below 7kg, but the beams weight would changes much with stringer number differs when the beams number is more than 7. While the stringers has little effect on beams weight when the beams number is less than 6. This is because of the thickness of the laminate only can increase in 2mm grade, and also because of the minimum height of beam '80mm' was given in Chapter 5.1.5. Some extra thickness and height will cause the total weight increases while the beams number increases.

5.1.6 Result and conclusion

Following the way of the metallic door weight calculation, the weight of the composite door was calculated out.

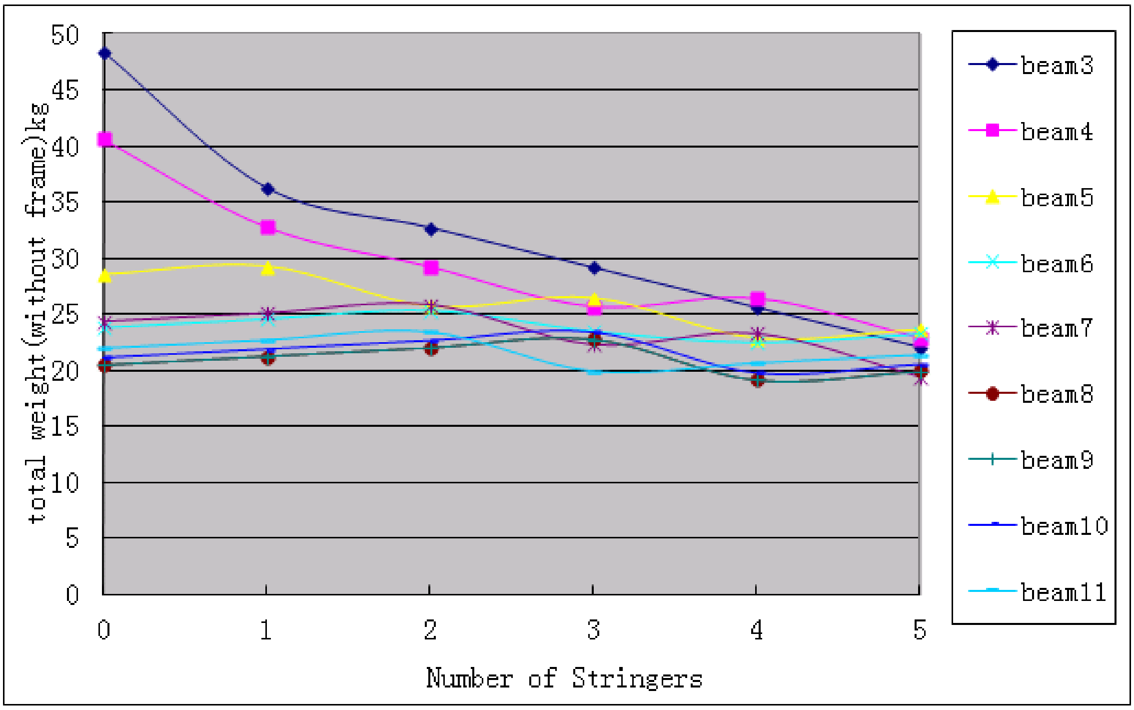
1) The weight contribution to structure



Graph 5-5 Weight Contribution to Structure in Case of 2 and 5 Stringers

From the Graph 5-5 it also can be concluded that the skin contributes more weight to the structure than the beams as the same as the metallic door. And the stringers number has a great effect on skin weight.

2) The weight of door structure (without frame)



Graph 5-6 Total Weight of Structure (without door frame)

It can be seen that the weight of the structure doesn't change smoothly while beams or stringers changes. Actually, this is because the composite thickness of each member can't change continuously like metallic.

From Graph 5-6, it can be seen the weight can keeps below 25kg while the beams number no less than 7 or the stringer number is more than 3. As the weight is affected more by the thickness of the skin, it also can be concluded that when the short edge of skin panel is less than 250mm the structure weight can keeps below 25kg, and the minimum weight can reache below 20kg.

5.1.7 Door structure model

Like the metallic door, the structure weight can keep below 25kg when the beam number is more than 6, or the stringer number is more than 4. And also considering of the stop fail matter and the manufacture problem and the structure should be thick enough for mechanism installation. Then, the door structure with 7 beams and 4 stringers is selected again to study. The geometry of the beams calculated by Matlab, as Appendix A.2.6 shows. The geometry is shown in Figure 5-1. According to FEM analysis, although the stress meets the result of theory calculation and the failure indices, the displacement of the structure is too big which can cause sealing problem and the max strain is too large while end stop failed. Therefore, in order to improve the stiffness property, the dimensions of the door structure is modified as Figure 5-2 shows.

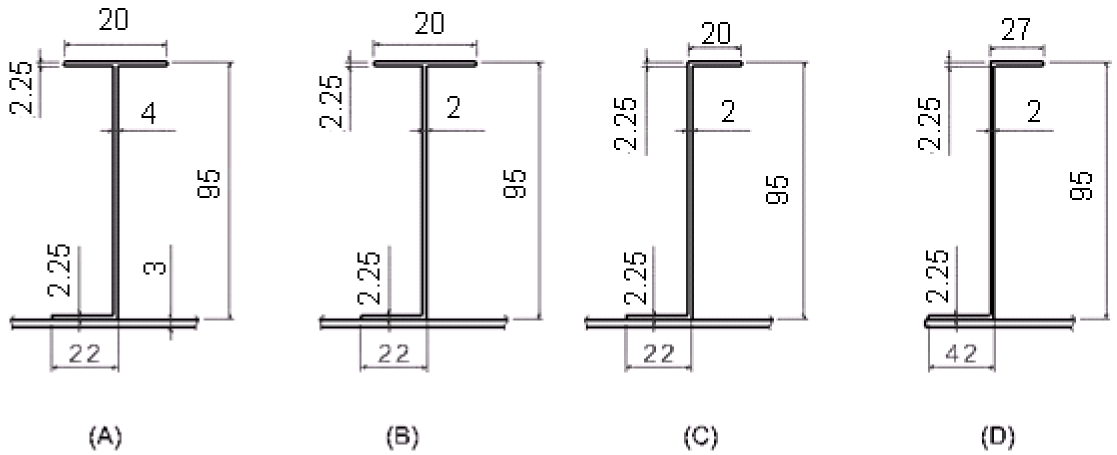


Figure 5-1 Geometry of Theory Calculaton

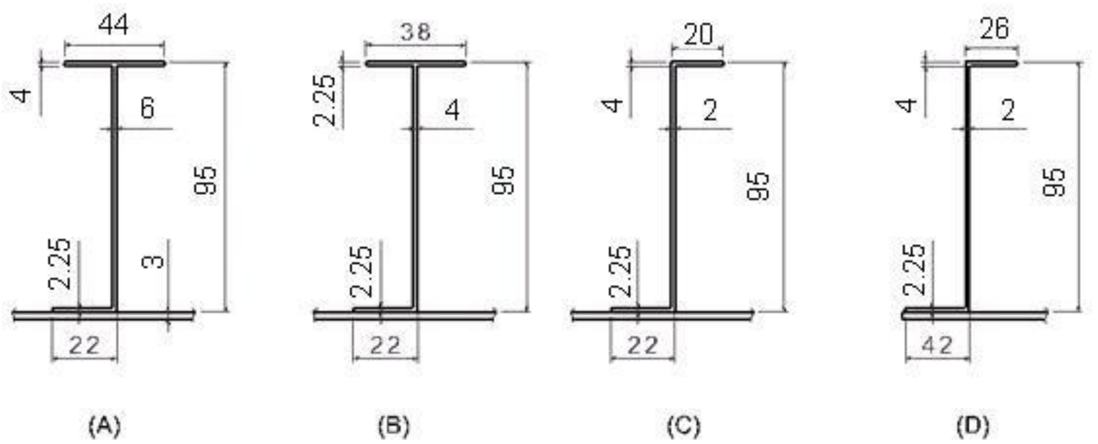


Figure 5-2 Geometry of Modification

(A)The skin thickness and the end beams dimension;

(B)The 5 middle beams dimension;

(C)The 4 stringers dimension;

(NOTE: only NO1 and NO.4 stringer were modified)

(D) The frame works dimension

The 3D CATIA model looks like the metallic model, but the dimensions are slightly different from the metallic one.

The weight of the modified CATIA structure model is shown in Table 5-2:

Table 5-2 Weight of Modified CATIA Structure Model of Composite Door

	component	skin	end beam	middle beam	stringer	frame	total
Theory model	Weight(kg)	10.3	2.24	2.75	3.67	3.56	22.63
	Percent(%)	45.5	9.9	12.2	16.7	15.7	
Modified model	Weight(kg)	10.3	3.08	4.87	3.76	4.3	26.31
	Percent(%)	39	11.8	18.5	14.3	16.4	

From table 5-2, it can be seen that the skin also contributes most of the weight to the structure.

5.2 FEM analysis of composite door structure

Similar to the metallic door, the skin, the beam, the stringer, the stop and frame web are using the 2D shell element. The flanges of the beams, stringers and frame are using 1D rod model element. For the 2D shell, the laminates are applied as the element properties and the equivalent properties of the Max.Rec.0 are applied to the 1D rod element.

5.2.1 Boundary constraint:

The boundary constraint of FEM model is like metallic door, but the laminate layup direction is defined additionally.

5.3 Result and conclusion

According to the FEM analysis of theory composite door structure, it can be seen from Table 5-3 that the stress is similar to the theory calculation result. The failure indices is satisfied the failure criteria, which can means the strength meet the design criteria. But as the table 5-5shows the max displacement under ΔP is 6.5mm, and While the displacement of the beams is 5mm, and when one stop fails, the max displacement can reach 9.9 mm. Actually it is too large for sealing consideration. Additionally, the strain of the four corners under $2.5\Delta P$ and the strain of frame when end stop fails under $1.5\Delta P$ exceed the strain limit $4000\mu\varepsilon$.

Then, in order to improve the stiffness of the door, the structure is modified which has been described in Chapter 5.1.7 in details.

The displacement of modified composite door structure is similar to the metallic door according to FEM analysis. The strain can almost meet the limit $4000\mu\varepsilon$ requirement, but the weight of the composite door is nearly 20% lighter than the metallic door.

5.3.1 Result comparison with theory calculation

All of the analysis in this part is based on the LINEAR solution type.

The tension、compression、shear member

Table 5-3 Stresses Comparison of Theory Model

Pressure load	member		theory stress (Mpa)	FEM max stress (Mpa)	allowable stress (Mpa)	Failure indices
$3\Delta P$	tension member		375	435	460	0.75
$2.5\Delta P$	Compression member		328	380	670(middle beam) 700(end beam)	0.4
$2.5\Delta P$	shear member	end beam	85	98	395	0.3
$2.5\Delta P$		middle beam	116	132	395	0.4

Table 5-4 Stresses Comparison of Modified Model

Pressure load	member		theory stress (Mpa)	FEM stress (Mpa)	allowable stress (Mpa)
$3\Delta P$	tension member		375	420	460
$2.5\Delta P$	Compression member		328	225	670(middle beam) 700(end beam)
$2.5\Delta P$	shear member	end beam	52	62	395
$2.5\Delta P$		middle beam	58	66	395

From Table 5-3, it can be seen that the stress of theory model is similar to the theory calculation stress, and the failure indices is satisfied with the failure criteria, which means the strength meet the design criteria. And from Table 5-4, it can be seen that the stress of modified model is lower than the theory model, especially the shear stress.

The displacement result

The displacement of theory and modified model in different situation is listed in Table 5-5, and the displacement nephogram can be seen in Figure 5-3 and Figure 5-4.

Table 5-5 Displacement of composite door structure

Model	Pressure load	Displacement(mm)		
		max	max of beam	sealing area
theory model	Δp	6.3	5	5
	Δp (fail-safe)	9.9	6.7	9.9
modified model	Δp	4.3	3.1	3.1
	Δp (fail-safe)	7.2	4.4	7.2

As it can been seen that the stiffness performance of modified model is much better than the theory model, and the displacement of modified model is similar to the metallic door. The max displacement of sealing area under working load is about 3mm, which is quite reasonable for sealing consideration.

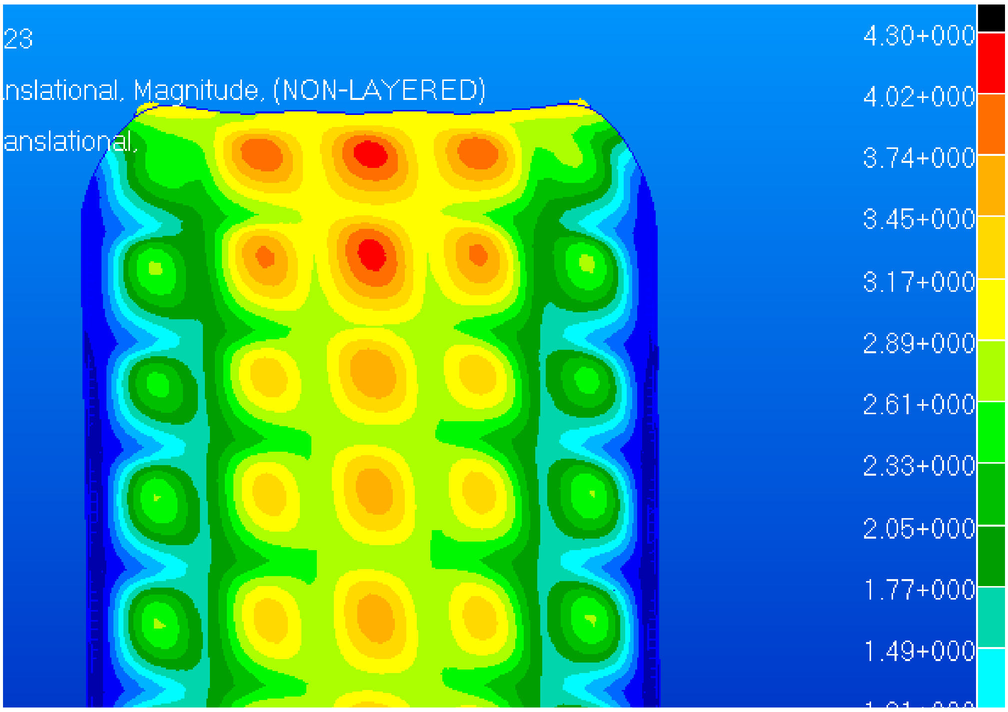


Figure 5-3 Max Displacement of Modified Model under ΔP

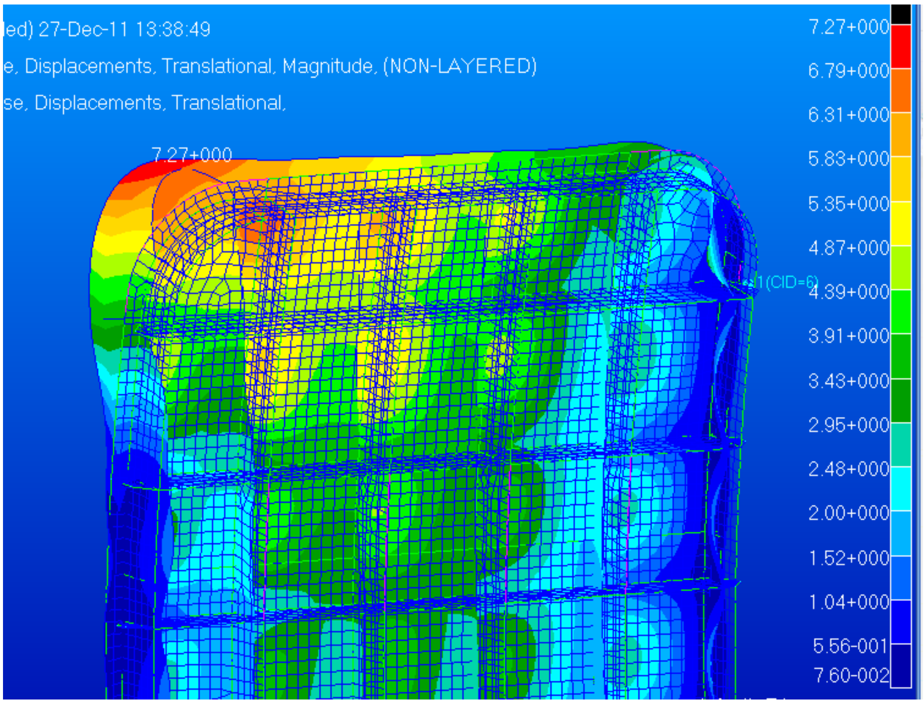


Figure 5-4 Max Displacement of End Stop Failure of Modified Model under ΔP

The fail-safe analysis result

As investigated in chapter 4, it is know that it would be much more serious when the end beam stop failed than other stops, so in this part, the study concentrated on the case of end beam stop failed.

Although the max stress of theory model is reasonable comparing with the allowable stress of tension member, the max strain is quite beyond the limit $4000\mu\varepsilon$. So, the frame inner flange was also reinforced while the beams were intensified. The max strain of modified model is quite close to the limit strain as shown in table 5-6 and figures below.

Table 5-6 FEM Analysis Result of One End Stop Failed

model	Pressure load	max stress (MPa)	max failure indices	max strain ($\mu\varepsilon$)
theory model	$1.5\Delta P$	763	0.88	5640
modified model	$1.5\Delta P$	573	0.64	4102
	ΔP	382	0.43	2870

1) The stress analysis

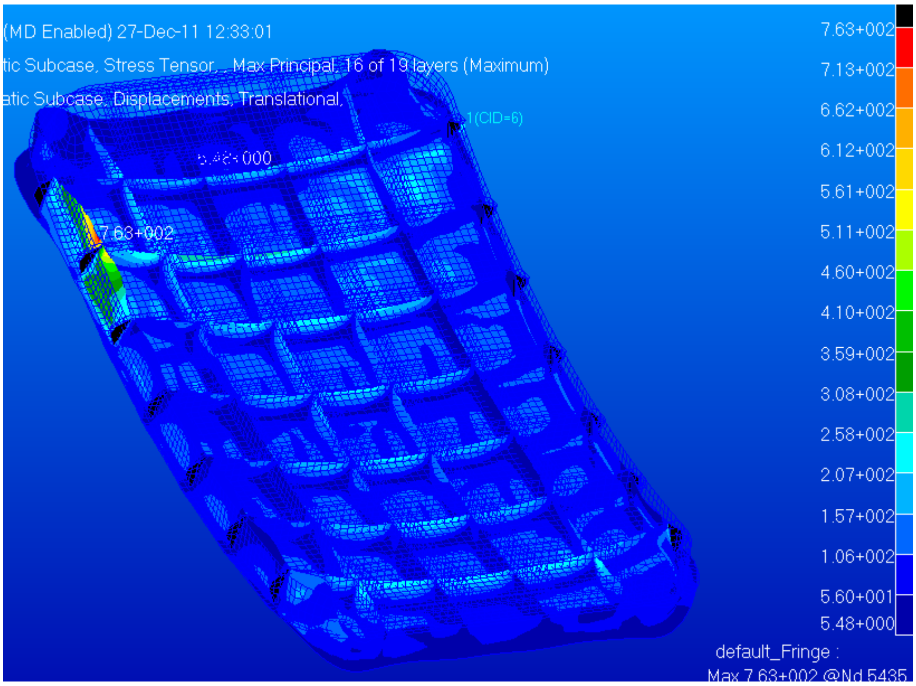


Figure 5-5 Max Principal Stress of End Stop Failed under $1.5\Delta P$ (theory model)

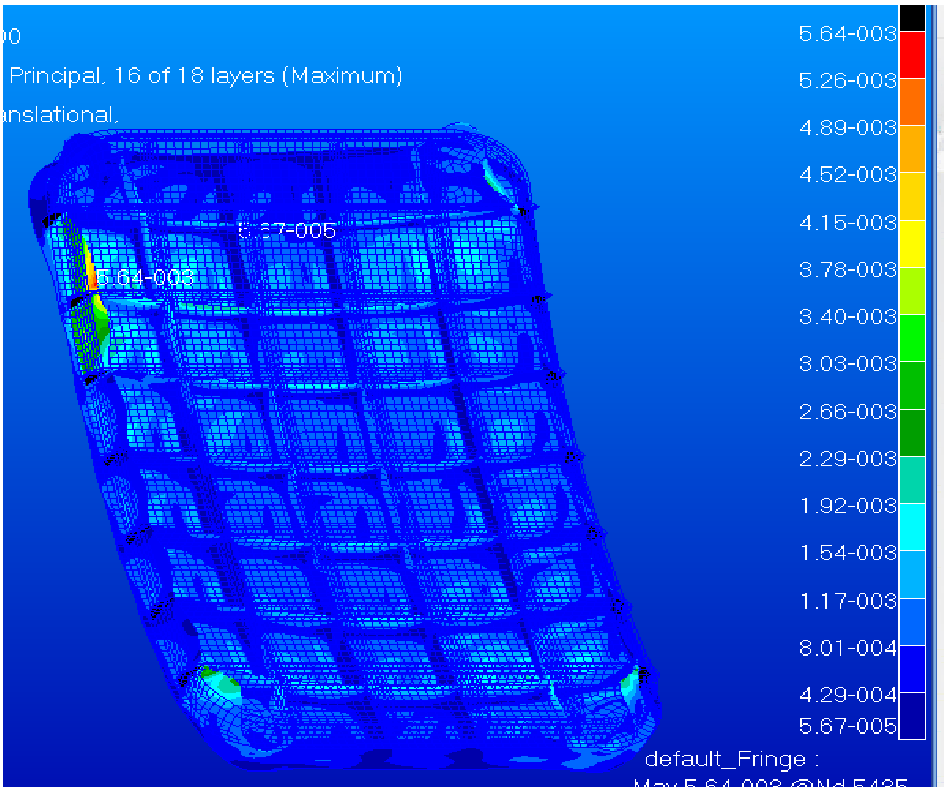


Figure 5-6 Strain of End Stop Failed under $1.5\Delta P$ (theory model)

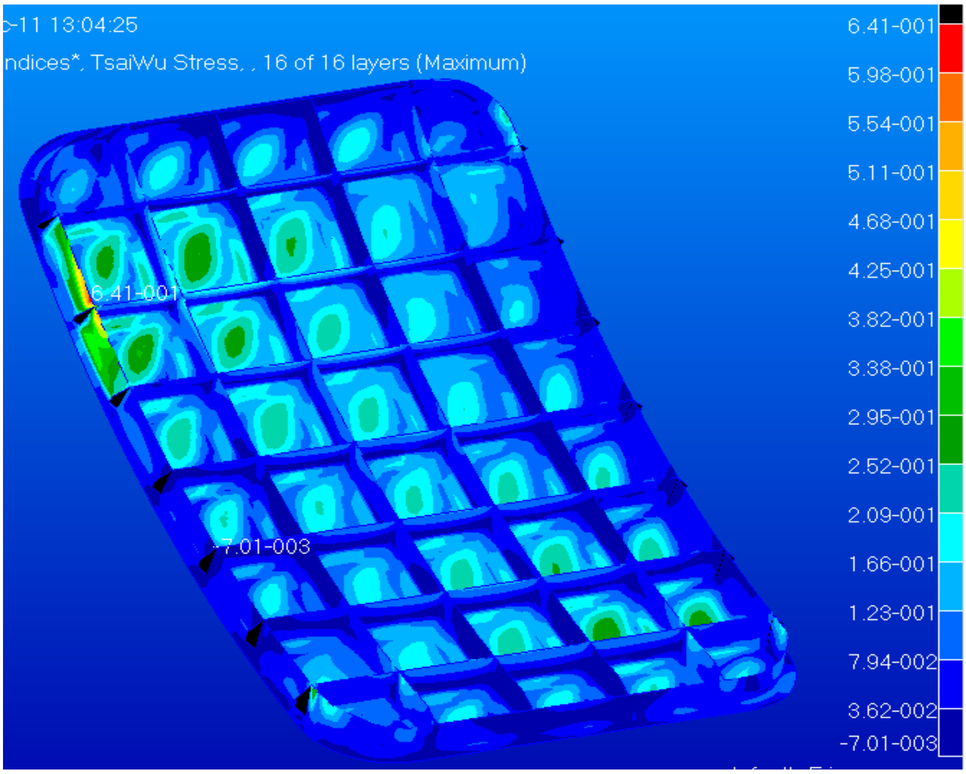


Figure 5-7 Failure indices of end stop failed under $1.5\Delta P$ (modified model)

The load reaction

Table 5-7 Beam Stop Reaction Force under $3\Delta P$

	Beam stop reaction force		
	Total load F(N)	End beam stop reaction load F1(N)	Middle beam stop reaction load F1(N)
theory	344400	31721	22657
FEM	358774	34003	24230

Table 5-8 Beam Stop Reaction Force When One Stop Failed under $1.5\Delta P$

member	max stop reaction force (N)
end beam stop	40,566

The force load reaction is similar to the theory calculation and the metallic door.

5.3.2 Conclusion and comparison with metallic door

In this chapter, the composite type A door structure is designed following the standard way generated from chapter 4, it can be conclude with the result of metallic door that applying 7 beams and 4 stringers for type A door is reasonable and almost the best choice for both metallic and composite door because of considering of manufacture and fail-safe.

As the thickness of laminate only changes in 1mm grade, the skin for different combination maybe can apply the same thickness, and such problem also exists in beam calculation as the thickness of the beam web only can increase in 2mm grade. So the weight of the composite door structure can't change as smoothly as the metallic door. However, some features of the composite door also can be generated as below:

- When the stringers number is more than 4 or the beams number is more than 6, the skin thickness can keeps below 4mm.
- The beams weight is affected by stringers because of shear buckling consideration while the beams number is more than 6, so the stringers number more than 3 would be better for beam weight reduction.
- Same as the metallic door, the skin contributes much more weight than other members to the door structure.
- According theory calculation, the weight of type A composite door structure (without frame) can keeps below 25kg while the beams number is no less than 7 or the stringer number is more than 3, and the minimum weight can reach below 20kg.

Comparing with metallic door, the composite door can save nearly 20% weight than the metallic door while the stiffness is similar, meanwhile the strength performance is much better than the metallic door.

6 Conclusion and recommendation

The aim of this thesis is to investigate the different types of pressure retaining doors and past aircraft accidents which involved the failure of doors, in order to identify the common and different aspects of these doors and key factors of door design. And then undertake the structure design of a typical pressure retaining door using metallic and composite materials, in order to discover a standard way of door structure design and the factors affecting the weight of the door structure, and to compare the metallic door structure with the composite structure.

Generally the pressure retaining door is divided into a plug-type and unplug-type of door. The former are normally located in the cabin area while the latter are usually the main cargo doors. Although fatal accidents have mostly involved unplug-type doors, there are also some other issues related to plug-type doors, such as the weight and stiffness requirements. Finally the structure of a horizontal slide type A door has been selected as the study target because of its wide use in modern aircraft and its critical requirements of weight and stiffness.

In the study of structure design, both the theory calculation and FEM analysis method were applied during the metallic and composite door structure design.

The step of theory calculation is first to simplify the door structure into skin, beams and stringers, and assume a range number of beams and stringers for the structure. For each combination of the beams and stringers, the optimised weight of the structure is calculated, and then identified the best combination with the lightest weight.

The step of FEM analysis is to construct an entire FEM model with Patran, and analyse with Nastran, and then modify the structure if necessary and compare it with theory calculation.

According to the structure design of metallic and composite doors, the features of the door structure and the key factors of structure weight have been studied, and generally can be described as:

- The skin contributes much more weight than other members to the door structure, especially when the beams and stringers numbers are fewer. As the skin thickness is related to the short edge width of the skin panel divided by beams and stringers to a great extent, the maximum distance of beams or stringers should be less than 250mm. This means that for type A door the beams number should be no less than seven and the stringers should be no less than four, which also mean the thickness of the skin is below 3mm for the aluminium door and 4mm for the composite door.

- The weight of a type A metallic door structure (without frame) can be kept below 30kg while the skin thickness is less than 3mm. The weight of a type A composite door structure (without frame) can be kept below 25kg while the skin thickness is less than 4mm. For the type A door with seven beams and four stringers, the weight percentage of the skin to the door structure can be 40%~50%.

- Beam is another contributor to the door structure weight and contributes about 25% to the total structure weight. The elements which can affect the weight of beam are worked out, i.e. the width of beam outer flange 'b', the web thickness 't_2', the outer flange thickness 't_3' have a negative effect on weight reduction, while the area of inner flange 'at_1', and the height of beam 'h' have a positive effect on minimizing beam weight; however, the effect of skin thickness on beam weight is not apparent.

- From the FEM analysis of a fail-safe case, it is known that the failure situation is much more serious when the stop of the end beam failed, and also the force load concentration is much higher when the end stop failed than when the middle stops failed, and the force is higher than the normal situation under $3\Delta P$.

According to comparisons of metallic and composite doors, it can be seen that the composite door is nearly 20% lighter than the metallic door while the stiffness is similar and strength performance is much better than the metallic door. Therefore, composite is really a good candidate for future aircraft door structure.

However, the main disadvantage of composite material for door structure is damage-tolerance, as the door can be easily impacted on while loading cargo or passengers; the defect is difficult to see when the delamination has occurred inside the composite material and the strength has been greatly reduced, especially for the compressive members.

It can be seen that both the metallic and composite doors can meet stress requirements as the design procedure is based on stress criteria; however, for composite door the stiffness is not enough for sealing consideration. In this thesis, the composite door was modified to improve the stiffness during the FEM analysis stage. Actually, as the stiffness of door is quite clearly related to the stiffness of the beams, adding the stiffness calculation of beams during the theory calculation stage is recommended, which perhaps can make the design method more reasonable and accurate.

As the skin is the biggest contributor to the weight, rather than other members, further work on weight reduction should be concentrated on the skin. As the analysis result shows, the skin thickness is related to the short edge of the skin panel which is divided by beams and stringers, so some lower stiffeners could be added to minimize the size of skin panel instead of beams and stringers to reduce the skin weight.

Finally, a structure test is recommended to verify the standard door structure design method and a comparison of the results of metallic and composite material.

REFERENCES

1. Michael Chun-Yung Niu. Airframe structural design: practical design information and data on aircraft structures. Commilit Press Ltd, Burbank California 1997; P74, P417-428.
2. Metallic Materials Properties Development and Standardization (MMPDS), Scientific Report. U.S. Department of Transportation Federal Aviation Administration, 2003.3-26,3-293.
3. Michael Chun-Yung Niu. Composite airframe structures. Commilit Press Ltd, Burbank California 1992; P18
4. Jean-Louis Espes.Technology Breakthrough – Eurocopter Produces the Worldwide first all-Composite Airplane door in one piece, Donauworth, DE, 2004.
5. http://www.airshow.com.cn/en/article/yjxx/2006-05-31/9607.html
6. Canadair Regional Jet 100/200 – Doors
7. http://www.flickr.com/photos/flightblogger/2652115016/
8. http://www.flyertalk.com/forum/trip-reports/975448-ac-milk-run-yyz-yvr-77l-j.html
9. http://www.flightglobal.com/airspace/media/civilaviation1949-2006cutaways/lockheed-l-1011-tristar-cargo-door-cutaway-8836.aspx
10. Senger, Stefan, Device for raising and lowering the passenger door of an aircraft, patent, Donauworth, DE, 2003.
11. http://processfab.com/spv-10.aspx
12. http://en.wikipedia.org/wiki/American_Airlines_Flight_96
13. Turkish Airlines DC-10, TC-JAV. Report on the accident in the Ermenonville Forest, France on 3 March 1974. French Secretariat of State for Transport, 1976.

14. http://www.thefreelibrary.com/Door+opens+as+ScotAirways+aircraft+travels+down+runway+for+takeoff.-a0114177295

15. http://en.wikipedia.org/wiki/File:United_Airlines_Flight_811_Cargo_hole_2.JPG

16. http://www.flightglobal.com/blogs/flightblogger/2007/11/taking-stock-a-787-update-illu.html

17. Dr. Jan Roskam, Dr. Chuan-Tau Edward Lan. Airplane Aerodynamics and Performance. DARcorporation, USA, 1997.

18. ESDU 71005, Buckling of flat plates in shear

19. ESDU 71013, Elastic direct stresses and deflections for flat rectangular plates under uniformly distributed normal pressure

20. Qiu Hongbo. Analysis and optimal design of a composite lower wing panel with cutout, thesis, Cranfield University, 2010.

21. Guo shijun. College of Aeronautics Laminate Analysis, Cranfield university. Stressing Data Sheet, AVT-AVD Cranfield college of aeronautics, 1999.

22. ESDU80023, Buckling of rectangular specially orthotropic plates.

23. STRESSING DATA SHEETS, Cranfield College of Aeronautics, AVT-AVD, 1999

24. M.J.BOUAB. Door design with glare material. Thesis, Cranfield University. 2003.

25. Aircraft design manual- NO.10-the structure design. China Aviation Industry Print 2000.10

26. MSC Company, MSC Patran 2010 user manual

27. Jane’s All the world’s Aircraft 2004-2005

28. http://en.wikipedia.org/

29. http://www.airbus.com/

30. http://www.boeing.com

31. Chen Rong. Conceptual Design of a Family of Aircraft. Thesis, Cranfield University. 2009.

32. http://baike.techweb.com.cn/doc-view-9842.shtml

Appendix A

A.1 Design of metallic door structure

A.1.1 Load distribution calculation on beams

As described in chapter 3.3, the working load is:

$$\Delta P = 8.17 PSI = 0.056 Mpa$$

If the rate of total load for end beams (B1) and middle beams (B2) carrying can be denoted by k_1, k_2, then they can be presented as follows:

$$k_1 = \frac{h1 + \dfrac{(h - 2 \times h1)}{2 \times (N - 1)}}{h} \qquad \textbf{Equation A-1}$$

$$k_2 = \frac{h - 2 \times h1}{h \times (N - 1)} \qquad \textbf{Equation A-2}$$

The uniform distribution load of end beam (B1) and middle beam (B2) can be presented as:

$$q(B1) = k_1 \times A \times \Delta P / L = k_1 \times h \times \Delta P = 0.1064 k_1 (N / m) \qquad \textbf{Equation A-3}$$

$$q(B2) = k_2 \times A \times \Delta P / L = k_2 \times h \times \Delta P = 0.1064 k_2 (N / m) \qquad \textbf{Equation A-4}$$

According to the load criteria, the uniform distribution load for each beam member takes is as below:

Compression and shear members:

$$q(B_{C1}) = 2.5 q(B1) = 0.266 k_1 \; ; \quad q(B_{C2}) = 2.5 q(B2) = 0.266 k_2$$

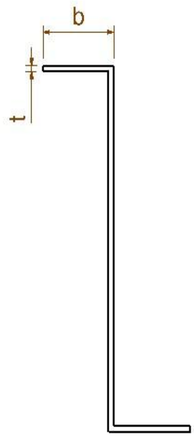
Tension members:

$$q(B_{T1}) = 3q(B1) = 0.3192k_1;\quad q(B_{T2}) = 3q(B2) = 0.3192k_2$$

Then, according to the ultimate bending moment Equation 4-1, Equation 4-2, the ultimate bending moment and ultimate shear force is calculated out, and they are shown in table 4-1.

A.1.2 Calculation of flange buckling stress

The inner flange of the beam boundary can be treated as one edge free and one simply supported, for it, K=0.58



$$\sigma_{CR} = KE_t\left(\frac{t}{b}\right)^2 \qquad \textbf{Equation A-5}$$

$$\therefore \quad \frac{\sigma_{CR}}{E_t} = 0.58\left(\frac{t}{b}\right)^2$$

According the value $\frac{1}{\varepsilon_n}\frac{\sigma_{CR}}{E_t}$, and the

CENERALISED CURVES FOR BULKLING (figure A-1) find out the corresponding $\frac{f}{f_n}$.

$$f = \sigma_{CR} = \frac{f}{f_n} \times f_n \qquad \textbf{Equation A-6}$$

For American standard material 7050-T7451:

$$m = \frac{4.258t_2}{f_{tu} - t_2} - 0.347 = 35.85 \qquad \textbf{Equation A-7}$$

——（provided by my supervisor P. Stocking）

$$f_n = \sigma_R\left(\frac{m\varepsilon_R E}{\sigma_R}\right)^{-1/(m-1)} \qquad \textbf{Equation A-8}$$

$$\frac{1}{\varepsilon_R} = \frac{E}{f_n}$$ **Equation A-9**

- **7050-T7451 property**

f_{tu} =76000(psi) ——Ultimate Tensile Strength

t_2 =68000(psi)——Tensile Yield Strength

E =71700——Modulus of Elasticity

$\varepsilon_R{}^{/}$ =0.001， ε_R =0.002

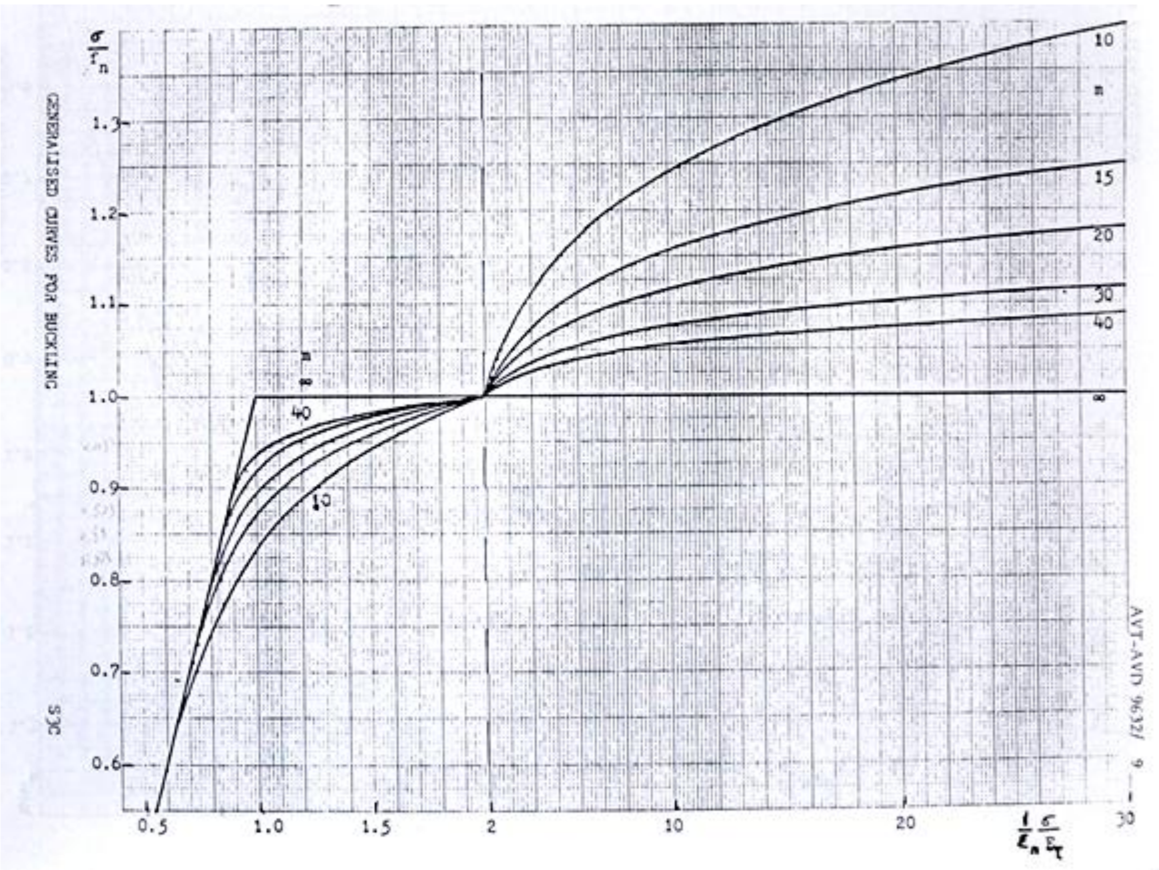


Figure A-1 CENERALISED CURVES FOR BULKLING [23]

From the above Equations and process, the beam flange buckling stress against the value $\frac{t}{b}$ is studied out in table A-1 and described in Graph 4-1.

Table A-1 Beam Flange Ultimate Buckling Stress against $\frac{t}{b}$

material	f_n	$\frac{1}{\varepsilon_n}$	t	b	$\frac{t}{b}$	$\frac{\sigma_{CR}}{E_t}$	$\frac{1}{\varepsilon_n}\frac{\sigma_{CR}}{E_t}$	$\frac{f}{f_n}$	f
7050-T7451	438	163.5	2	27	0.074	0.0032	0.52	0.53	232.14
7050-T7451	438	163.5	2	26	0.077	0.0034	0.56	0.565	247.47
7050-T7451	438	163.5	2	25	0.08	0.0037	0.61	0.6	262.8
7050-T7451	438	163.5	2	22	0.09	0.0048	0.78	0.78	341.64
7050-T7451	438	163.5	2	21	0.095	0.0053	0.86	0.87	381.06
7050-T7451	438	163.5	2	20	0.1	0.0058	0.95	0.915	400.77
7050-T7451	438	163.5	2	18	0.11	0.0072	1.17	0.955	418.29
7050-T7451	438	163.5	2	17	0.1176	0.008	1.31	0.97	424.86
7050-T7451	438	163.5	2	16	0.125	0.0091	1.48	0.98	429.24

A.1.3 Calculation of beam web shear buckling stress

This part is to find out the minimum thickness of beam web and maximum beam height according the consideration of shear buckling. It means the value when the applied stress equal to the shear buckling stress.

- **The applied stress**

The maximum shear load is in the tip of each beam as figure 4-4 and table 4-1 shows.

So the applied stress:

$f_{xy}{}' = \frac{F_{\max 1}}{t_2 h}$ (for the both ends beams) **Equation A-10**

$f_{xy2}{}' = \frac{F_{\max 2}}{t_2 h}$ (for the middle beams) **Equation A-11**

- **The buckling stress**

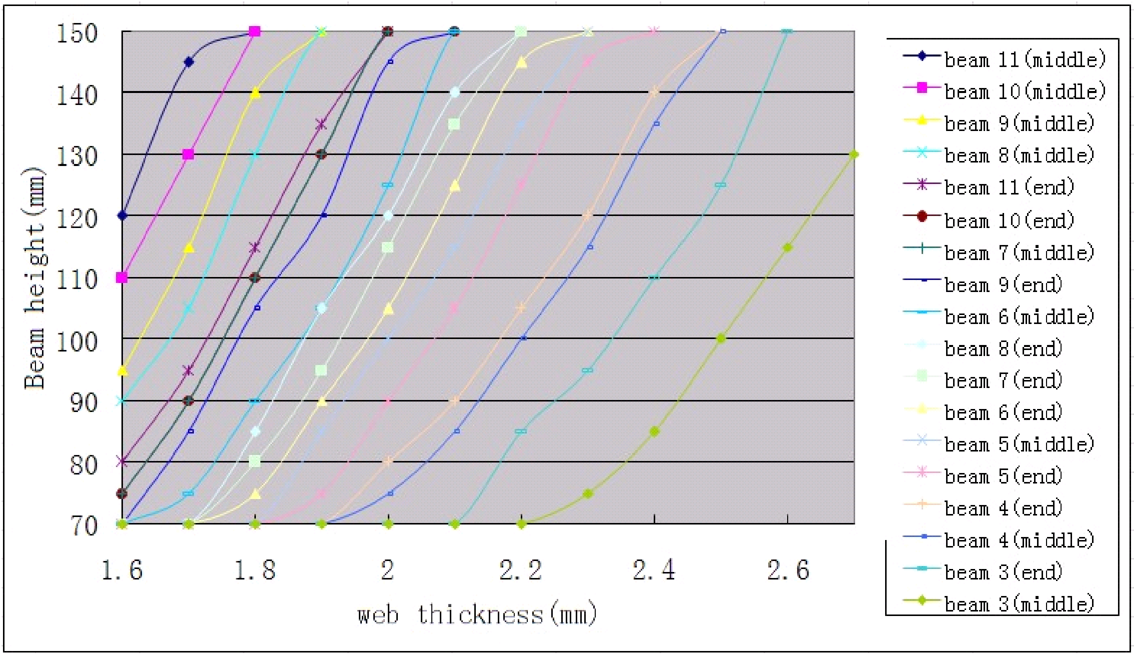
The calculation follows the ESDU 71005.

$f_{xye} = 0.91/\left(1-\upsilon^2\right)KE(t/b)^2$ **Equation A-12**

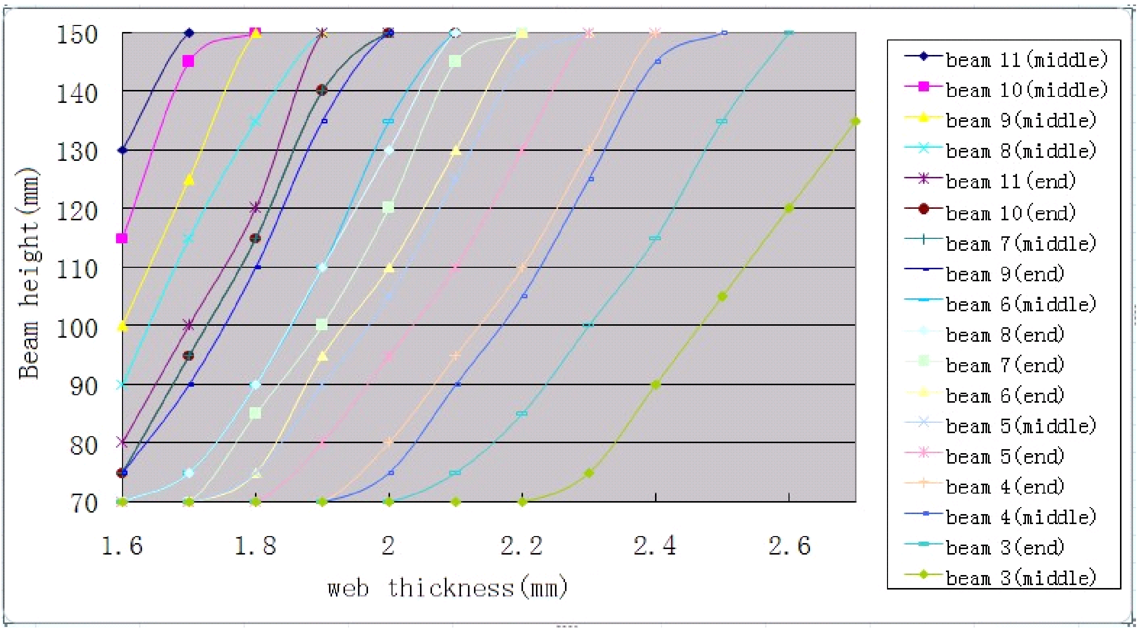
$f_{xy} = \eta f_{xye}$ **Equation A-13**

K——elastic buckling stress coeffient defined by $f_{xye} = 0.91/\left(1-\upsilon^2\right)KE(t/b)^2$, it can be search by figure 1 of ESDU 71005 according to $\frac{b}{h}$, and use the simply-supported curve.

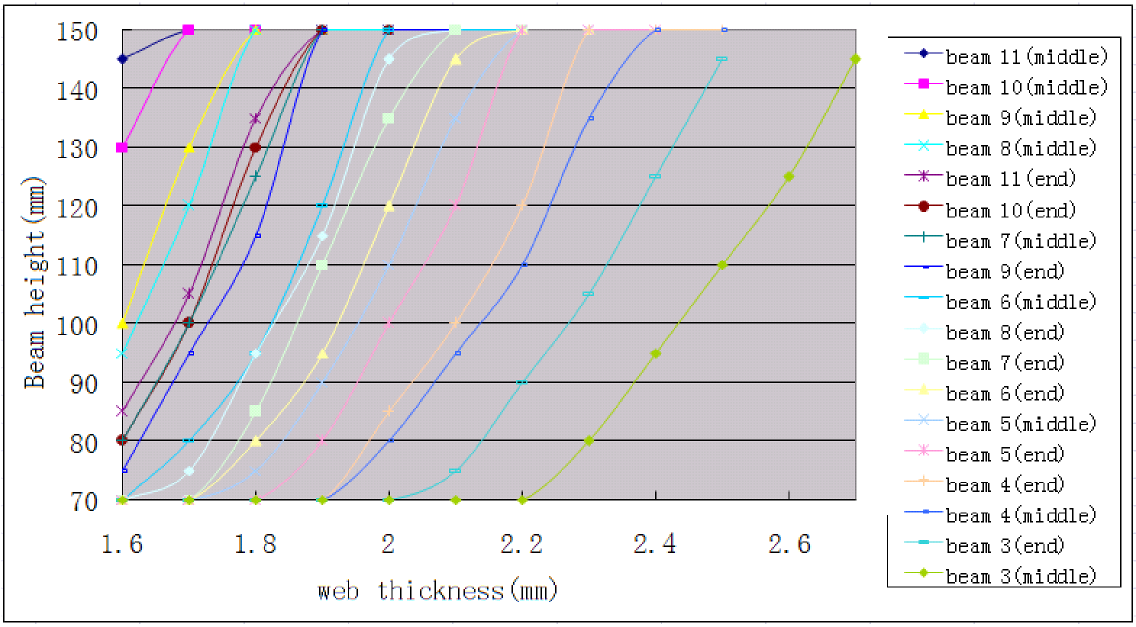
η——plasticity reduction factor defined by $f_{xy} = \eta f_{xye}$, it can be search by figure 1 of ESDU 71005 according to $\frac{f_{xye}}{f_n}$, and m.



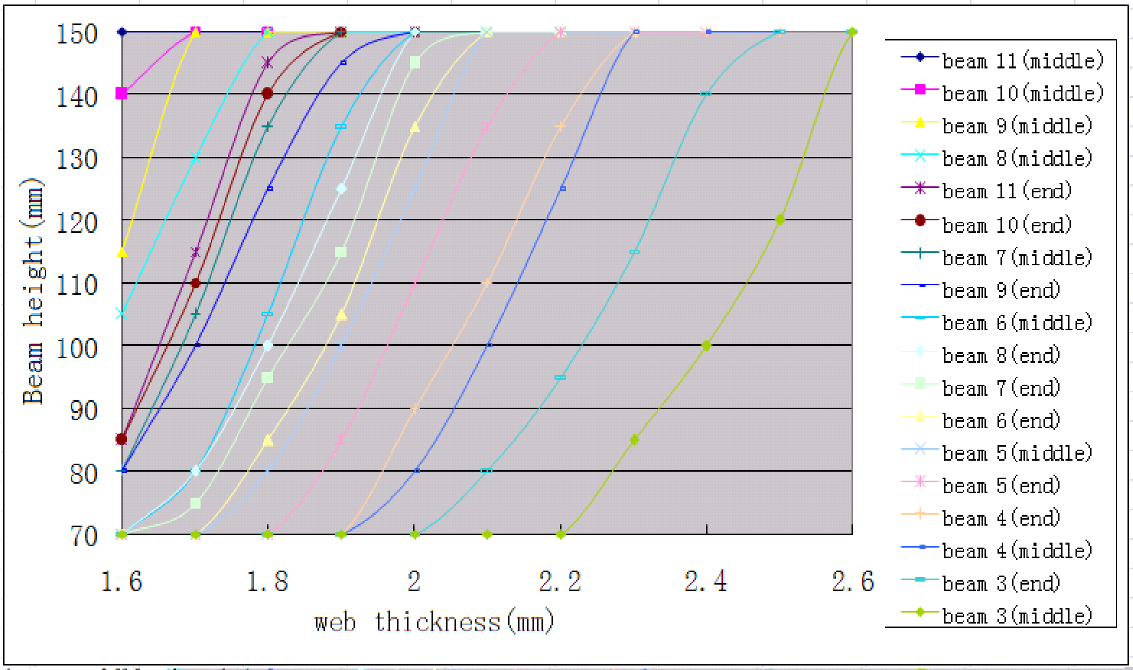
Graph A-1 Beam Height against Beam Web Thickness of 1 Stringers



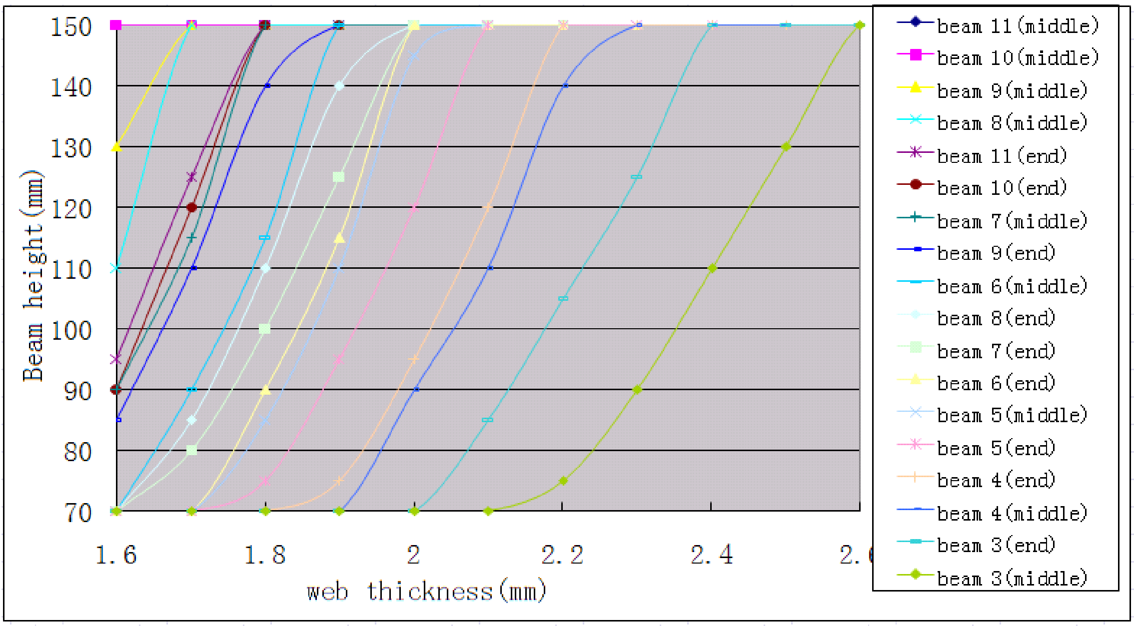
Graph A-2 Beam Height against Beam Web Thickness of 2 Stringers



Graph A-3 Beam Height against Beam Web Thickness of 3 Stringers



Graph A-4 Beam Height against Beam Web Thickness of 4 Stringers



Graph A-5 Beam Height against Beam Web Thickness of 5 Stringers

A.1.4 Skin thickness calculation

Table A-2 Skin Thickness of Metallic Door

fixed in translation and free in rotation														
$3\Delta P$	Beam× Stringer	a	b	t	r	E	$\frac{a}{b}$	$\frac{b}{t}$	$\left(\frac{rp}{E}\right)^{1/4}$	$\frac{b}{t}\left(r\frac{p}{E}\right)^{1/4}$	$\frac{f_{C2}}{p}\left(\frac{t}{b}\right)^{2}$	$p\left(\frac{b}{t}\right)^{2}$	f	Weight（kg）
0.168	3×5	730	180	2.42	0.979	72400	4.06	74.38	0.039	2.89	0.5	929.44	464.72	14.16
0.168	3×4	730	216	2.9	0.979	72400	3.38	74.48	0.039	2.89	0.5	932.01	466.01	16.97
0.168	3×3	730	270	3.62	0.979	72400	2.7	74.59	0.039	2.90	0.5	934.59	467.29	21.18
0.168	3×2	730	360	4.8	0.979	72400	2.03	75	0.039	2.91	0.495	945.00	467.78	28.09
0.168	3×1	730	540	6.68	0.979	72400	1.35	80.84	0.039	3.14	0.425	1097.85	466.59	39.09
0.168	3×0	1080	730	9.3	0.979	72400	1.48	78.49	0.039	3.05	0.454	1035.12	469.94	54.42
0.168	4×5	487	180	2.42	0.979	72400	2.71	74.38	0.039	2.89	0.5	929.44	464.72	14.16
0.168	4×4	487	216	2.9	0.979	72400	2.25	74.48	0.039	2.89	0.5	932.01	466.01	16.97
0.168	4×3	487	270	3.55	0.979	72400	1.8	76.06	0.039	2.95	0.48	971.81	466.47	20.77
0.168	4×2	487	360	4.46	0.979	72400	1.35	80.72	0.039	3.13	0.43	1094.57	465.19	26.1
0.168	4×1	540	487	5.46	0.979	72400	1.11	89.19	0.039	3.46	0.35	1336.54	467.79	32
0.168	4×0	1080	487	6.54	0.979	72400	2.22	74.46	0.039	2.89	0.5	931.56	465.78	38.27
0.168	5×5	365	180	2.4	0.979	72400	2.03	75	0.039	2.91	0.495	945.00	467.78	14.0
0.168	5×4	365	216	2.84	0.979	72400	1.69	76.06	0.039	2.95	0.48	971.81	466.47	16.6

0.168	5×3	365	270	3.34	0.979	72400	1.35	80.84	0.039	3.14	0.425	1097.85	466.59	19.5
0.168	5×2	365	360	3.86	0.979	72400	1.01	93.26	0.039	3.62	0.32	1461.30	467.62	22.6
0.168	5×1	540	365	4.66	0.979	72400	1.48	78.33	0.039	3.04	0.454	1030.68	467.93	27.3
0.168	5×0	1080	365	4.88	0.979	72400	2.96	74.8	0.039	2.90	0.5	939.84	469.92	28.6
0.168	6×5	300	180	2.36	0.979	72400	1.7	76.27	0.039	2.96	0.48	977.31	469.11	13.8
0.168	6×4	300	216	2.7	0.979	72400	1.4	80	0.039	3.11	0.435	1075.20	467.71	15.8
0.168	6×3	300	270	3.02	0.979	72400	1.1	89.4	0.039	3.47	0.35	1342.84	469.99	17.7
0.168	6×2	360	300	3.52	0.979	72400	1.2	85.23	0.039	3.31	0.385	1220.30	469.82	20.6
0.168	6×1	540	300	4	0.979	72400	1.8	75	0.039	2.91	0.49	945.00	463.05	23.4
0.168	6×0	1080	300	4.04	0.979	72400	3.6	74.26	0.039	2.88	0.5	926.38	463.19	23.6
0.168	7×5	250	180	2.25	0.979	72400	1.4	80	0.022	1.75	0.435	1075.20	467.71	13.17
0.168	7×4	250	216	2.55	0.979	72400	1.2	84.71	0.022	1.85	0.385	1205.41	464.08	14.92
0.168	7×3	270	250	2.8	0.979	72400	1.1	89.29	0.022	1.95	0.35	1339.29	468.75	16.39
0.168	7×2	360	250	3.12	0.979	72400	1.4	80.13	0.022	1.75	0.435	1078.65	469.21	18.26
0.168	7×1	540	250	3.35	0.979	72400	2.2	74.63	0.022	1.63	0.5	935.62	467.81	19.60
0.168	7×0	1080	250	3.35	0.979	72400	4.3	74.63	0.022	1.63	0.5	935.62	467.81	19.60
0.168	8×5	214	180	2.12	0.979	72400	1.19	84.91	0.022	1.85	0.385	1211.11	466.28	12.41
0.168	8×4	216	214	2.3	0.979	72400	1.01	93.04	0.022	2.03	0.32	1454.39	465.41	13.46
0.168	8×3	270	214	2.58	0.979	72400	1.26	82.95	0.022	1.81	0.405	1155.84	468.11	15.10
0.168	8×2	360	214	2.82	0.979	72400	1.68	75.89	0.022	1.66	0.48	967.47	464.39	16.50

0.168	8×1	540	214	2.88	0.979	72400	2.52	74.31	0.022	1.62	0.5	927.58	463.79	16.85
0.168	8×0	1080	214	2.88	0.979	72400	5.05	74.31	0.022	1.62	0.5	927.58	463.79	16.85
0.168	9×5	198	180	2.02	0.979	72400	1.1	89.11	0.022	1.95	0.35	1333.99	466.90	11.82
0.168	9×4	216	198	2.21	0.979	72400	1.09	89.59	0.022	1.96	0.345	1348.51	465.24	12.93
0.168	9×3	270	198	2.45	0.979	72400	1.36	80.82	0.022	1.76	0.427	1097.25	468.53	14.34
0.168	9×2	360	198	2.62	0.979	72400	1.82	75.57	0.022	1.65	0.487	959.48	467.27	15.33
0.168	9×1	540	198	2.66	0.979	72400	2.73	74.44	0.022	1.63	0.5	930.84	465.42	15.57
0.168	9×0	1080	198	2.66	0.979	72400	5.45	74.44	0.022	1.63	0.5	930.84	465.42	15.57
0.168	10×5	180	176	1.89	0.979	72400	1.02	93.12	0.022	2.03	0.32	1456.84	466.19	11.06
0.168	10×4	216	176	2.1	0.979	72400	1.23	83.81	0.022	1.83	0.395	1180.04	466.12	12.29
0.168	10×3	270	176	2.26	0.979	72400	1.53	77.88	0.022	1.70	0.46	1018.87	468.68	13.23
0.168	10×2	360	176	2.35	0.979	72400	2.05	74.89	0.022	1.64	0.495	942.32	466.45	13.75
0.168	10×1	540	176	2.36	0.979	72400	3.07	74.58	0.022	1.63	0.5	934.35	467.18	13.81
0.168	10×0	1080	176	2.36	0.979	72400	6.14	74.58	0.022	1.63	0.5	934.35	467.18	13.81
0.168	11×5	180	158	1.81	0.979	72400	1.14	87.29	0.022	1.91	0.365	1280.17	467.26	10.59
0.168	11×4	216	158	1.98	0.979	72400	1.37	79.8	0.022	1.74	0.435	1069.78	465.35	11.59
0.168	11×3	270	158	2.08	0.979	72400	1.71	75.96	0.022	1.66	0.48	969.39	465.31	12.17
0.168	11×2	360	158	2.12	0.979	72400	2.28	74.53	0.022	1.63	0.5	933.15	466.58	12.41
0.168	11×1	540	158	2.12	0.979	72400	3.42	74.53	0.022	1.63	0.5	933.15	466.58	12.41
0.168	11×0	1080	158	2.12	0.979	72400	6.84	74.53	0.022	1.63	0.5	933.15	466.58	12.41

a——length of plate m

b——width of plate m

E——Young's modulus N/m2

f_C——maximum total stress at centre N/m2

f_c——stress at middle surface corresponding to f_C N/m2

f_D——maximum total stress on diagonals N/m2

f_d——stress at middle surface corresponding to f_D N/m2

f_E——total stress at mid-point of long edge N/m2

f_e——stress at middle surface corresponding to f_E N/m2

p——normal pressure on plate N/m2

r——ratio $\left(1-\upsilon^2\right)/0.91$ (when $\upsilon=0.3$, $r=1$)

A.1.5 Programme for beam weight calculation

A MATLAB program as follows was written to calculate this:

(Assume the structure is 6 beams and 2 stringer, material: 7050-T7451)

- Input

```
m25=4704      % maximum bending moment for compression member 2.5ΔP
m3=5645          % maximum bending moment for tension member 3ΔP
for t1=1.5:0.1:3          %the range of beam inner flange thickness (mm)
   for t2=1.8:0.1:3.5         %the range of beam web thickness (mm)
      for t3=1.8:0.2:3.5        %the range of beam outer flange thickness(mm)
         for t4=2.8               %the thickness of skin(mm)
            for a=20:2:60           %the width of beam inner flange(mm)
               for b=22:2:50          %the width of beam outer flange(mm)
                  for h=80:2:130    %the height of beam
                     f=t1/a;           %the value of thickness to width of beam inner flange
                     aa1=(a-t2)*t1;          %the area of beam inner flange
                  y1=h-t1/2;
                     aa2=(h-t1-t3)*t2;        %area of beam web
                     y2=(h-t1+t2)/2;
                     aa3=(b-t2)*t3;           %area of beam outer flange
                     y3=t3/2;
                     aa4=30*t4*t4;            %area of skin
                     y4=-t4/2;
                     aa=aa1+aa2+aa3+aa4;                    %A=∑A
                     aay=aa1*y1+aa2*y2+aa3*y3+aa4*y4;          %A ȳ=∑Ay
                     avey=aay/aa;%average;                  %ȳ=∑Ay/∑A
```

```
                    ixx=aa1*y1*y1+aa2*y2*y2+aa3*y3*y3+aa4*y4*y4+(a-
t2)*t1*t1*t1*t1/12+t2*(h-t1-t3)*(h-t1-t3)*(h-t1-t3)/12+(b-
t2)*t3*t3*t3/12+30*t4*t4*t4*t4/12;
```

% $I_{xx} = \sum Ay^2 + \sum bh^3/12$

```
                    ina=ixx-aa*avey*avey;
```

% $I_{NA} = I_{xx} - A\bar{y}^2$

```
inner beam stress=1000*m25*(h-avey)/ina;
```

% Maximum applied compression stress= $\dfrac{My}{I_{NA}}$

```
Outer beam stress=1000*m3*avey/ina;
```

% Maximum applied tension stress= $\dfrac{My}{I_{NA}}$

- Load criteria and condition

```
If inner beam stress<372&&outer beam stress<524&&aa<420 &&f>0.049
```

% f>0.049 and inner beam stress<372, and outer beam stress<524

- Output

```
 c=[f,a,b,t1,t2,t3,t4,h,aa,uppstress,lowstress]
                    c1(k,4)=t2;
                    c1(k,8)=aa;
                     k=k+1;
                   end
                end
             end
          end
       end
    end
  end
 end
 %k=k-1;
 x=c1(:,4);
 y=c1(:,8);
 plot(x,y,'*')%,hold  on
```

A.1.6 Weight calculation of door structure

As refers to the total weight of the structure in this theory design period, only the weight of beams, stringers and skin were considered.

So, the total weight of the door structure:

$$W_{Total} = W_{Beams} + W_{Skin} + W_{Stringers} \qquad \textbf{Equation A-14}$$

The beam weight:

$$W_{Beams} = 2 \times W_{endbeam} + (N-2) \times W_{middlebeam}$$

The skin weight:

$$W_{Skin} = t_4 \times A_{Skin} \times 2.8 = t_4 \times 1.12 \times 1.9 \times 2.8 = 5.85 t_4 kg$$

The stringer weight:

As the stringer doesn't take much load, so in this thesis, no matter how many stringers includes the thickness of stringer is assumed as 1.2 mm as the flange is assumed as 22mm. So for the weight of each stringer:

$$W_{Stringer} = 2.8 \times 1.9 \times 0.16 \times 1.2 = 1.02 kg$$

Table A-3 shows the beam and total weight calculation of door structure with 7 Beams.

Table A-3 Weight Calculation of 7 Beams

stringer NO.			0	1	2	3	4	5	0	1	2	3	4	5
skin thickness			3.35	3.35	3.12	2.8	2.55	2.25	3.35	3.35	3.12	2.8	2.55	2.25
maximum bending moment		Bean web thickness	beam height						Minimum area					
midlle beam	19600	1.6	75	75	75	80	80	90				365	365	365
	19600	1.7	90	90	95	100	105	115	333	333	330	327	325	323
	19600	1.8	105	110	115	125	135	150	330.7	329.3	329	329	329.5	329.5
	19600	1.9	125	130	140	150	150	150	335.4	335.4	336	336	336	
	19600	2	145	150	150	150	150	150	342	341.6				
	25480	1.7	70	70	70	70	75	80						472
	25480	1.8	80	80	85	85	95	100	461.8	461.8	438.2	438.2	402	388
	25480	1.9	95	95	100	110	115	125	399.7	399.7	393.5	386.2	384	382
	25480	2	110	115	120	135	145	150	391.5	390	389.2	389	389	389.2
	25480	2.1	130	135	145	150	150	150	395.5	395.5	395.7			
Total beam cross-section area									2436.5	2426.5	2423.4	2407.4	2393	2379
total beam weight									7.64	7.61	7.60	7.55	7.50	7.46
total skin weight									19.60	19.60	18.26	16.39	14.92	13.17
total stringer weight									0.0	1.0	2.0	3.0	4.0	5.0
total structure weight(without frame)									27.25	28.21	27.86	26.94	26.43	25.63

Table A-4 Beam Weight and Skin Weight

	total beam weight(kg)						Skin weight(kg)	
Stringer NO. / Beam NO	0	1	2	3	4	5	2	5
3			5.63			5.63	28.09	14.16
4			6.21			6.21	26.10	14.16
5	6.76	6.75	6.73	6.71	6.64	6.62	22.59	14.04
6			7.18			7.18	20.60	13.81
7	7.64	7.61	7.60	7.55	7.50	7.46	18.26	13.17
8			7.99			7.99	16.50	12.41
9			8.32			8.32	15.33	11.82
10			8.76			8.76	13.75	11.06
11			9.19			9.19	12.41	10.59

Table A-5 Total Weight Calculation of Door Structure

Beam NO.	Beam Weight (kg)	skin weight(kg)						Stringer weight(kg)						total weight of door structure(kg)					
		Stringer NO.																	
		0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5
3	5.63	54.42	39.09	28.09	21.18	16.97	14.16	0	1	2	3	4	5	60.05	45.72	35.72	29.81	26.60	24.70
4	6.21	38.27	31.95	26.10	20.77	16.97	14.16	0	1	2	3	4	5	44.48	39.16	34.31	29.99	27.18	25.37
5	6.73	28.56	27.27	22.59	19.55	16.62	14.04	0	1	2	3	4	5	35.32	35.02	31.32	29.26	27.26	25.66
6	7.18	23.64	23.41	20.60	17.67	15.80	13.81	0	1	2	3	4	5	30.82	31.59	29.78	27.85	26.98	25.99
7	7.60	19.60	19.60	18.26	16.39	14.92	13.17	0	1	2	3	4	5	27.25	28.21	27.86	26.94	26.43	25.63
8	7.99	16.85	16.85	16.50	15.10	13.46	12.41	0	1	2	3	4	5	24.84	25.84	26.49	26.09	25.45	25.40
9	8.32	15.57	15.57	15.33	14.34	12.93	11.82	0	1	2	3	4	5	23.88	24.88	25.65	25.65	25.25	25.14
10	8.76	13.81	13.81	13.75	13.23	12.29	11.06	0	1	2	3	4	5	22.57	23.57	24.51	24.98	25.05	24.82
11	9.19	12.41	12.41	12.41	12.17	11.59	10.59	0	1	2	3	4	5	21.60	22.60	23.60	24.36	24.78	24.78

A.1.7 The stop reaction force load of one stop failed

- The stop reaction load of one end beam stop failed

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
2611	G	0.0	-5.463300E+00	1.034791E+04	0.0	0.0	0.0
2618	G	0.0	5.324792E+00	-1.034791E+04	0.0	0.0	0.0
14718	G	1.857248E+04	0.0	0.0	0.0	0.0	0.0
14739	G	1.265154E+04	0.0	0.0	0.0	0.0	0.0
14760	G	1.222779E+04	0.0	0.0	0.0	0.0	0.0
14781	G	1.180943E+04	0.0	0.0	0.0	0.0	0.0
14802	G	9.911845E+03	0.0	0.0	0.0	0.0	0.0
14823	G	8.748738E+03	0.0	0.0	0.0	0.0	0.0
14844	G	1.972812E+04	0.0	0.0	0.0	0.0	0.0
14867	G	1.976492E+04	0.0	0.0	0.0	0.0	0.0
14888	G	8.688621E+03	0.0	0.0	0.0	0.0	0.0
14909	G	9.510472E+03	0.0	0.0	0.0	0.0	0.0
14930	G	8.574048E+03	0.0	0.0	0.0	0.0	0.0
14951	G	-1.629514E+03	0.0	0.0	0.0	0.0	0.0
14972	G	4.056646E+04	0.0	0.0	0.0	0.0	0.0

MD NASTRAN JOB CREATED ON 10-NOV-11 AT 10:34:35 NOVEMBER 21, 2011 MD NASTRAN 7/

- The stop reaction load of one middle beam stop failed

F O R C E S O F S I N G L E - P O I N T C O N S T R A I N T

POINT ID.	TYPE	T1	T2	T3	R1	R2	R3
2611	G	0.0	1.562955E-01	9.314937E+03	0.0	0.0	0.0
2618	G	0.0	-2.547272E-01	-9.314938E+03	0.0	0.0	0.0
14718	G	2.022240E+04	0.0	0.0	0.0	0.0	0.0
14739	G	9.398230E+03	0.0	0.0	0.0	0.0	0.0
14760	G	1.023580E+04	0.0	0.0	0.0	0.0	0.0
14781	G	1.071272E+04	0.0	0.0	0.0	0.0	0.0
14802	G	1.015922E+04	0.0	0.0	0.0	0.0	0.0
14823	G	9.003943E+03	0.0	0.0	0.0	0.0	0.0
14844	G	1.996511E+04	0.0	0.0	0.0	0.0	0.0
14867	G	1.990937E+04	0.0	0.0	0.0	0.0	0.0
14888	G	8.817568E+03	0.0	0.0	0.0	0.0	0.0
14909	G	9.146456E+03	0.0	0.0	0.0	0.0	0.0
14930	G	1.712184E+04	0.0	0.0	0.0	0.0	0.0
14972	G	1.593756E+04	0.0	0.0	0.0	0.0	0.0
14993	G	1.876734E+04	0.0	0.0	0.0	0.0	0.0

MD NASTRAN JOB CREATED ON 10-NOV-11 AT 10:34:35 NOVEMBER 21, 2011 MD NASTRAN 7/1

A.2 Design of composite door structure

A.2.1 Applied composite material

1. Introduction

High strength Carbon/Epoxy unidirectional prepreg is applied for all members of the composite door structure, including the skin, the beams and the stringers and the frame.

The properties of High strength Carbon/Epoxy unidirectional prepreg is show in table A-6.

Table A-6 Properties of High strength Carbon/Epoxy unidirectional Prepreg

Notations	Properties	Values
E_1	Longitudinal Young's Modulus, MPa	140,000
E_2	Transverse Young's Modulus, MPa	10,000
G_{12}	In-plane shear Modulus, MPa	5,000
υ_{12}	Major Possions Ratio,	0.3
X_t	Ultimate Longitudinal tensile strength, MPa	1,500
X_c	Ultimate Longitudinal compressive strength, MPa	1,200
Y_t	Ultimate Transverse tensile strength, MPa	50
Y_c	Ultimate Transverse compressive strength, MPa	250
S	Ultimate In-plane shear strength, MPa	70
ρ	Density kg/m^3	1,600
$e_{x,t}$	Ultimate Longitudinal tensile strain, %	1.05
$e_{y,t}$	Ultimate Longitudinal compressive strain, %	0.5
t	Laminate thickness, mm	0.125

2. Layup

Further the laminate should be balanced, that is the arrangement of the plies should be symmetrical about the mid-depth.

Because of the effect of laminate thickness and the symmetrical arrangement, the thickness of the composite doesn't like the metallic can be continue, the applied thickness of the skin only can be changed in 1mm grade, while the thickness of beam web changed in 2mm grade. (Table A-7)

For the beam flange as the increase grade is too large for 4mm, another similar layup (48/40/12) was added for investigation. The details are in Table A-8.

Table A-7 Applied Composite Stacking Sequence and Thickness

remark	stacking sequence	Laminate thickness(mm)				thickness (mm)
		45°	0°	-45°	90°	
Quasi-isotropic	$\left(45^{\circ}/0^{\circ}/-45^{\circ}/90^{\circ}\right)_S$	0.125	0.125	0.125	0.125	1
		0.25	0.25	0.25	0.25	2
		0.375	0.375	0.375	0.375	3
		0.5	0.5	0.5	0.5	4
		0.625	0.625	0.625	0.625	5
		:	:	:	:	:
Max.Rec. ±45°	$\left(45^{\circ}_3/0^{\circ}/-45^{\circ}_3/90^{\circ}\right)_S$	0.375	0.125	0.375	0.125	2
		0.75	0.25	0.75	0.25	4
		1.125	0.375	1.125	0.375	6
		1.5	0.5	1.5	0.5	8

Table A-8 Applied Composite Stacking Sequence and Thickness

remark	Laminate layup/ stacking sequence	Laminate thickness(mm)				thickness (mm)
		45°	0°	-45°	90°	
Max.Rec.0°	(50/37.5/12.5)/ $\left(45^{\circ}/0^{\circ}/-45^{\circ}/90^{\circ}\right)_S$	0.375	1	0.375	0.25	4
		0.75	2	0.75	0.5	8
	(48/40/12)/ $\left(45^{\circ}_3/0^{\circ}/-45^{\circ}_3/90^{\circ}\right)_S$	0.625	1.5	0.625	0.375	6.25

3. Laminate property

The COALA programme is used to calculate the laminate property.

- Input parameter

➢ Material properties:

$(E_1 \quad E_2 \quad G_{12} \ \upsilon_{12} \quad)$

$(X_t \quad X_c \quad Y_t \quad Y_c \quad S \ )$

$(e_{x,t} \quad e_{x,c} \quad e_{y,t} \quad e_{x,c} \quad e_s)$ (%)

➢ Stacking sequence and thickness of laminate t

➢ Load Case

(T 1; T 2; T 3; c 1; c 2; c 3);

$(N_x; \ N_y; \ N_{xy}; \ M_x; \ M_y; \ M_{xy})$

- Failure indices

(HOFFMAN &&TSAI-WU&&TSAI-HILL&&MAX STRESS)<1

- Output

'A','B','D' Matrix

Laminate membrane equivalent engineering elastic constants：

$E_x \ E_y \quad M_x \quad M_y \quad \upsilon_{xy} \quad \upsilon_{yx} \quad G_{xy}$

➢ The applied stress of laminate can be calculated by equation A-15.

$$f = (N_x, N_y, N_{xy})/t \qquad \textbf{Equation A-15}$$

While the failure indices (HOFFMAN &&TSAI-WU&&TSAI-HILL&&MAX STRESS) access but less than 1. (Table A-9)

Table A-9 Laminate Properties

component	remark	layup	X direction stress (MPa)		Y direction stress (MPa)		shear stress (MPa)	E (MPa)		$\varepsilon(\mu\varepsilon)$	
		(0/±45/90)	tension	compression	tension	compression		E_x	E_y	ε_x	ε_y
skin	quasi-istropic	(25/50/25)	470	460	470	460	280	0.541	0.541	869.2	850.8
beam web	maxrec.45	(12.5/75/12.5)	315	330	315	330	395	0.379	0.379	830.8	870.4
flange	maxrec.0	(50/37.5/12.5)	740	700	300	325	230	0.828	0.363	894.2	826
		(48/40/12)	720	690	308	321	235	0.818	0.371	888.2	865

A.2.2 Calculation of composite Flange buckling stress

The 'D' metric of composite property was calculated by COALA.

According to ESDU 80023, the beam inner flange can be treated as:

Long plates subjected to biaxial load, sides simply-supported (C=2.0), like figure A-2 shows.

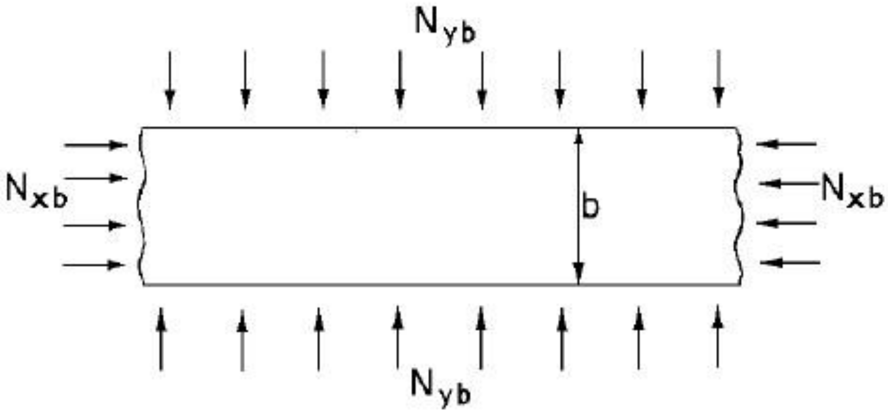


Figure A-2 Long plates subjected to biaxial load, sides simply-supported (C=2.0)

$$N_{xb} = \frac{K_0(D_{11}D_{22})^{1/2}}{b^2} + \frac{C\pi^2 D_0}{b^2}$$ **Equation A-16**

So the laminate compressive buckling stress is:

$$f_b = \frac{N_{xb}}{t} = \frac{K_0(D_{11}D_{22})^{1/2}}{b^2 t} + \frac{C\pi^2 D_0}{b^2 t}$$ **Equation A-17**

As $N_{yb} = 0$, the K_0 can be search from figure as 19.7.

So

$$f_b \cdot b^2 = \frac{19.7 \times (D_{11}D_{22})^{1/2}}{t} + \frac{2 \times \pi^2 D_0}{t}$$ **Equation A-18**

In order to investigate the relationship of buckling stress f and the flange width b, some extra laminate with other thickness which neglects the laminate thickness was inserted for analysis. The result is in table A-10 and graph 5-1.

And it can be fitting as equation:

$$f_b \cdot b^2 = 157588t^2 + 203919t - 249740$$ **Equation A-19**

So, the buckling stress is:

$$f_b = \frac{157588t^2 + 203919t - 249740}{b^2}$$ **Equation A-20**

Table A-10 Beam Flange Buckling Analysis

$f_b \cdot b^2$	795965.4	968100.9	1146494	1345045	1560085	1791131
t	2	2.25	2.4	2.6	2.8	3
$f_b \cdot b^2$	2037759	2300315	2578910	2975705.3	3872602.3	7187094
t	3.2	3.4	3.6	4	4.5	6.25

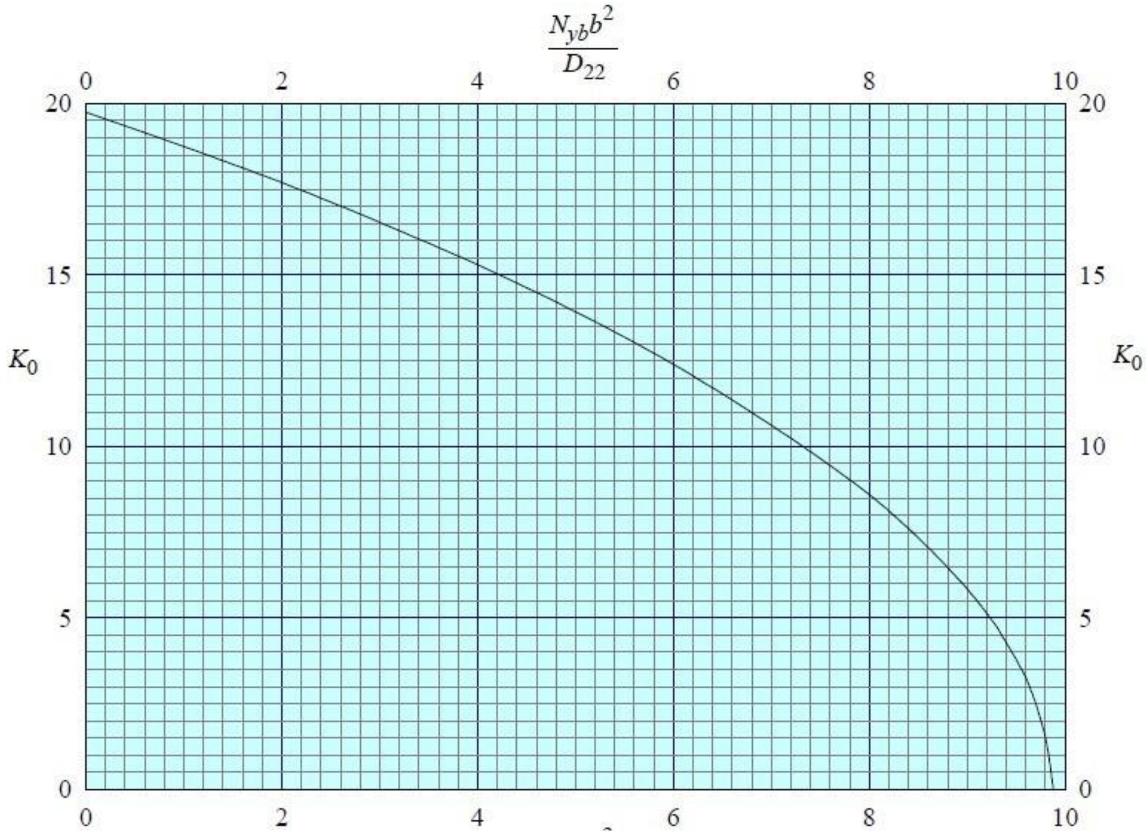


Figure A-3 Nyb COMPRESSIVE [22]

A.2.3 Calculation of web shear buckling stress

According to ESDU 80023, the beam web can be treated as all edges simply-supported, like figure A-4 shows.

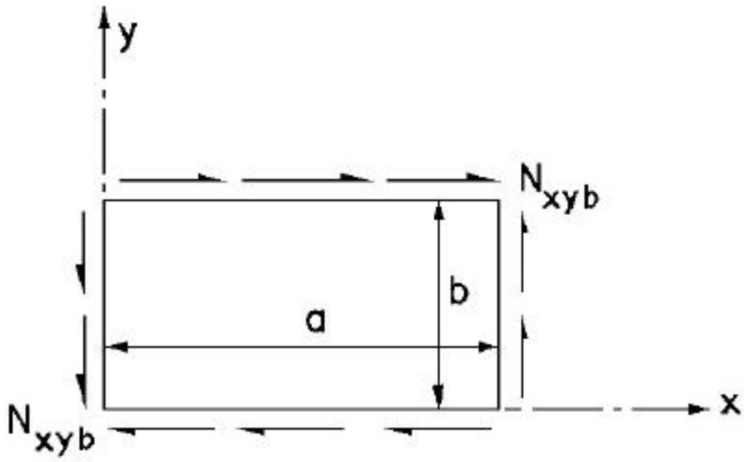


Figure A-4 Shear, all edges simply-supported

As the web is divided by stringers into several segments, so, the value of web height 'b' is assumed as 110mm while the value of web width 'a ' is assumed from 200 to 1100 in each step of 100mm.

So, the value of $\frac{a}{b}\left(\frac{D_{22}}{D_{11}}\right)^{1/4} > 1$, as table A-11 shows.

Table A-11 Web Shear Buckling Calculation of Composite

a	1000	900	800	700	600	500	400	300	200
b	110	110	110	110	110	110	110	110	110
$\frac{a}{b}$	9.09	8.18	7.27	6.36	5.45	4.55	3.64	2.73	1.82
$\frac{a}{b}\left(\frac{D_{22}}{D_{11}}\right)^{1/4}$	8.39	7.55	6.71	5.87	5.03	4.19	3.36	2.52	1.68

As the laminate value $\frac{D_0}{(D_{11}D_{22})^{1/2}}$ for different thickness is calculated as 2.0, although the 'D' metric is different from laminate thickness, the value $\frac{N_{xyb}ab}{(D_{11}D_{22})^{1/2}}$ can be searched as 134.

Then the web applied shear stress can be presented as:

$$f_{xy} = \frac{N_{xyb}}{t} = 134 \times \frac{(D_{11}D_{22})^{1/2}}{abt}$$

And $f_{xy} \cdot ab = 134 \times \frac{(D_{11}D_{22})^{1/2}}{t}$

Like the study of buckling stress, more laminates with other thickness were added to research the feature of web shear buckling, like table A-12 shows.

And it can be fitting as equation:

$$f_{xy} \cdot ab = 519846t^2 + 65681t - 50402$$ **Equation A-21**

So, the shear buckling stress can be presented as equation A-22:

$$f_{xy} \cdot = \frac{519846t^2 + 65681t - 50402}{ab}$$ **Equation A-22**

Table A-12 Web Shear Buckling Stress of Composite

t	2	2.2	2.4	2.6	2.8
$f_{xy} \cdot ab$	2150639	2602296	3096711	3634506	4215156
t	3	3.2	3.4	4	6
$f_{xy} \cdot ab$	4837797	5504959	6213937	8472628	19065654.18

A.2.4 Skin thickness calculation

Table A-13 Skin Thickness of Composite Door

$3\Delta P$	beams×stringers	Long edge (mm)	Short edge (mm)	skin thickness (mm)	max principal (MPa)	Displacement (mm)
0.168	3×5	730	180	3	452	5.75
0.168	3×4	730	216	4	379	5.02
0.168	3×3	730	270	5	374	5.99
0.168	3×2	730	360	5	482	12.9
0.168	3×1	730	540	7	449	13.8

0.168	3×0	1080	730	9	483	22.4
0.168	4×5	487	180	3	408	5.34
0.168	4×4	487	216	4	334	4.45
0.168	4×3	487	270	4	400	7.75
0.168	4×2	487	360	5	394	8.3
0.168	4×1	540	487	6	394	10.3
0.168	4×0	1080	487	8	428	13.4
0.168	5×5	365	180	3	351	4.54
0.168	5×4	365	216	3	401	6.5
0.168	5×3	365	270	4	356	5.56
0.168	5×2	365	360	4	450	7.85
0.168	5×1	540	365	5	414	7.87
0.168	5×0	1080	365	6	323	6.13
0.168	6×5	300	180	3	311	3.81
0.168	6×4	300	216	3	370	5.17
0.168	6×3	300	270	3	455	6.67
0.168	6×2	360	300	4	393	5.69
0.168	6×1	540	300	4	458	7.81
0.168	6×0	1080	300	4	479	9.14
0.168	7×5	250	180	2	475	5.89
0.168	7×4	250	216	3	338	3.98
0.168	7×3	270	250	3	409	5.14
0.168	7×2	360	250	4	321	3.69
0.168	7×1	540	250	4	332	4.37
0.168	7×0	1080	250	4	316	4.63

A.2.5 Weight calculation of composite door structure

Table A-14 Weight of Composite Door Structure

Beams NO	Stringers NO	Skin thickness	W_{Skin}	W_{Beams}	$W_{Stringers}$	W_{Total}
3	0	10	33.44	3.10	0	46.54
	1	7	23.41	2.71	0.75	33.87
	2	6	20.06	2.73	1.5	30.29
	3	5	16.72	2.74	2.25	26.72
	4	4	13.38	2.75	3	23.13
	5	3	10.03	2.76	3.75	19.55
4	0	8	26.75	3.75	0	38.50
	1	6	20.06	3.17	0.75	29.99
	2	5	16.72	3.18	1.5	26.41
	3	4	13.38	3.19	2.25	22.82
	4	4	13.38	3.19	3	23.57
	5	3	10.03	3.22	3.75	20.00
5	0	5	16.72	3.62	0	25.34
	1	5	16.72	3.62	0.75	26.09
	2	4	13.38	3.63	1.5	22.51
	3	4	13.38	3.64	2.25	23.26
	4	3	10.03	3.65	3	19.69
	5	3	10.03	3.65	3.75	20.44
6	0	4	13.38	4.13	0	21.50
	1	4	13.38	4.13	0.75	22.25
	2	4	13.38	4.13	1.5	23.00
	3	3	10.03	4.13	2.25	19.41
	4	3	10.03	4.11	3	20.15
	5	3	10.03	3.46	3.75	20.24
7	0	4	13.38	4.95		22.33
	1	4	13.38	4.95	0.75	23.08

	2	4	13.38	4.95	1.5	23.83
	3	3	10.03	4.95	2.25	20.23
	4	3	10.03	3.92	3	19.95
	5	2	6.69	3.93	3.75	16.37
8	0	3	10.03	4.90	0	17.93
	1	3	10.03	4.90	0.75	18.68
	2	3	10.03	4.90	1.5	19.43
	3	3	10.03	4.90	2.25	20.18
	4	3	10.03	4	3	20.03
	5	2	6.69	4	3.75	16.43
9	0	3	10.03	6.22	0	19.24
	1	3	10.03	6.22	0.75	19.99
	2	3	10.03	6.22	1.5	20.74
	3	3	10.03	4.38	2.25	19.66
	4	2	6.69	4.38	3	16.06
	5	2	6.69	3.98	3.75	16.41
10	0	3	10.03	6.94	0	19.97
	1	3	10.03	6.94	0.75	20.72
	2	3	10.03	6.94	1.5	21.47
	3	3	10.03	4.78	2.25	20.06
	4	2	6.69	4.33	3	16.01
	5	2	6.69	4.33	3.75	16.76
11	0	3	10.03	7.64	0	20.67
	1	3	10.03	7.64	0.75	21.42
	2	3	10.03	7.64	1.5	22.17
	3	2	6.69	5.20	2.25	16.14
	4	2	6.69	4.74	3	16.42
	5	2	6.69	4.73	3.75	17.16

A.2.6 Beam geometry calculation

Table A-15 Parameters of Beams

geometry		a mm	b mm	t_1 mm	t_2 mm	t_3 mm	t_4 mm	h mm	A_B mm^2	f_c MPa	f_{xy} MPa
theory model	end beam	20	22	2.25	4	2.25	3	95	438	538	197
	middle beam	20	22	2.25	2	2.25	3	95	266	696	418
modified model	end beam	40	22	4	6	2.25	3	95	704	263	88
	middle beam	38	22	2.25	4	2.25	3	95	479	328	141

A.2.7 FEM analysis of composite door

- **FEM analysis of Theory model**

1) Max principal stress (MPa)

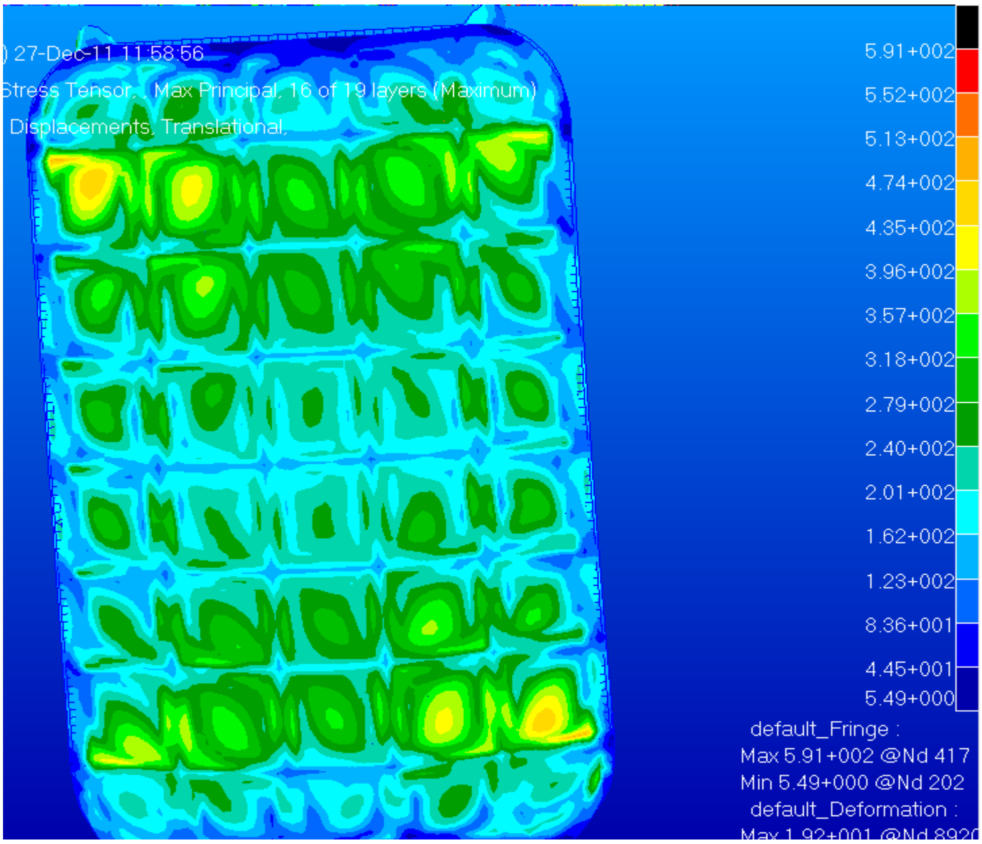


Figure A-5 Max Principal Stress under $3\Delta P$

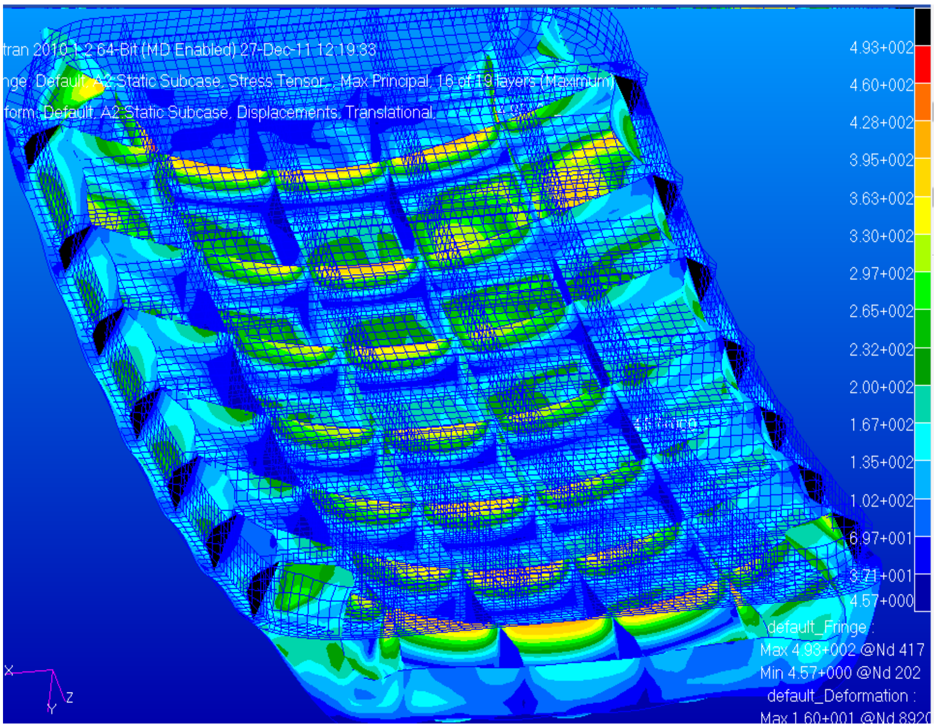


Figure A-6 Max Principal Stress under $2.5\Delta P$

2) The failure indices

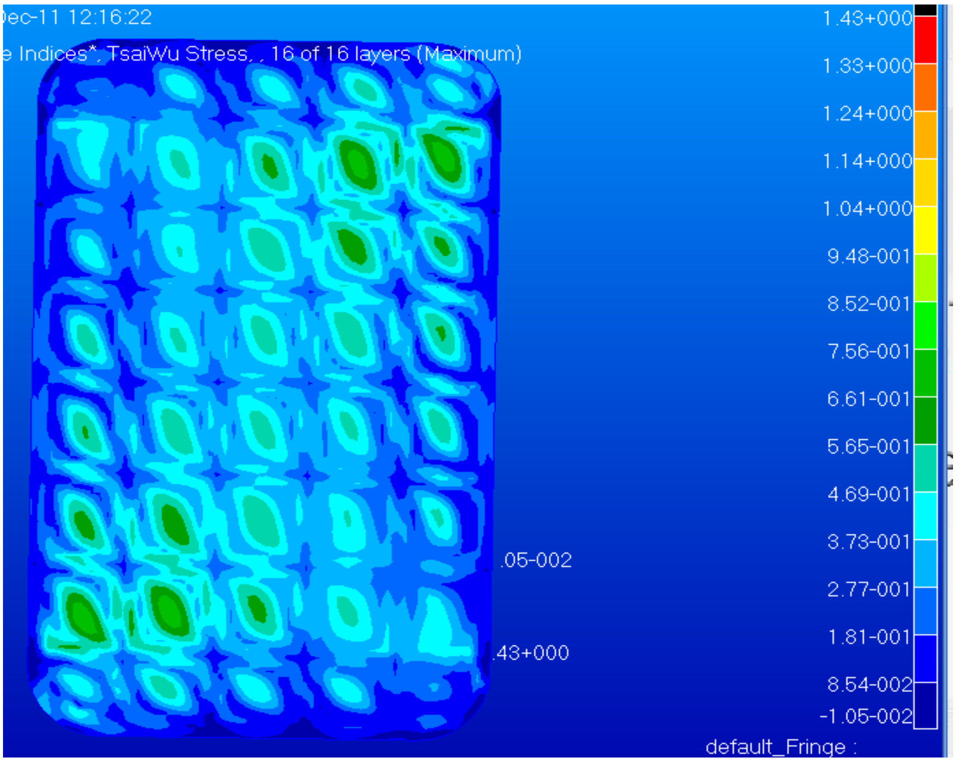


Figure A-7 Failure Indices under $3\Delta P$

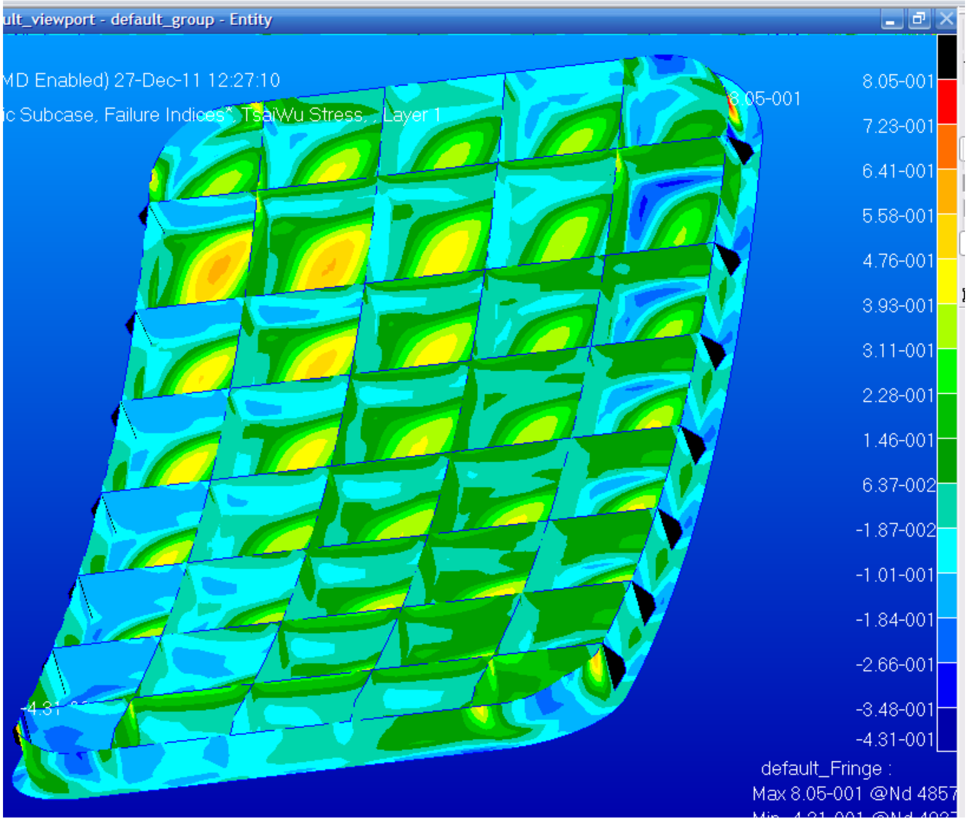


Figure A-8 Failure Indices under $2.5\Delta P$

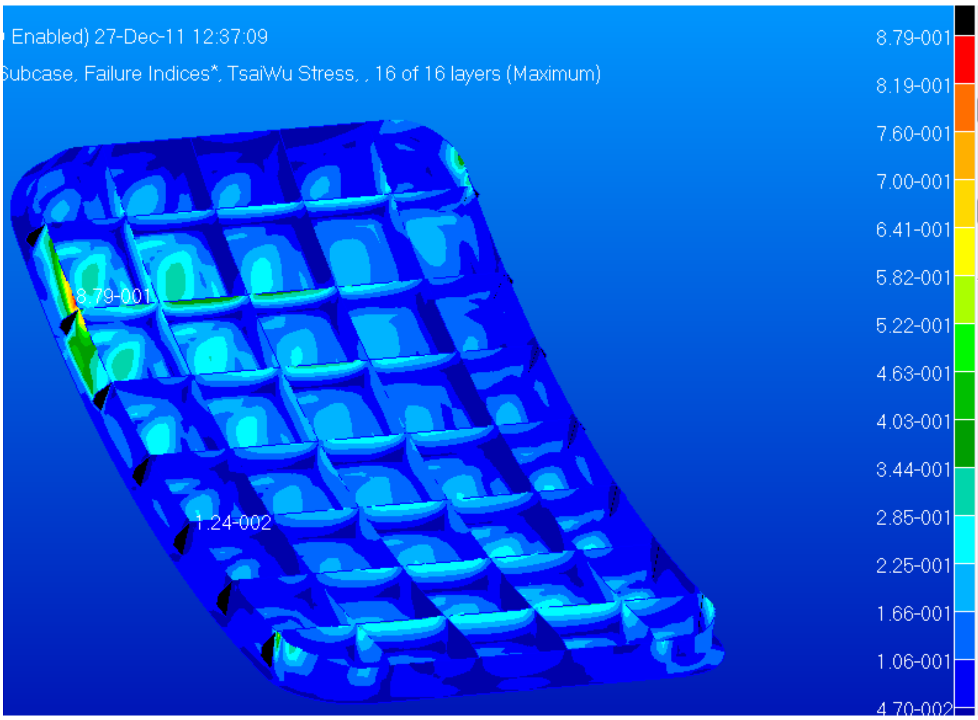


Figure A-9 Failure Indices of End Stop Failure under $1.5\Delta P$

- **FEM analysis of modified model**

The failure indices of modified model

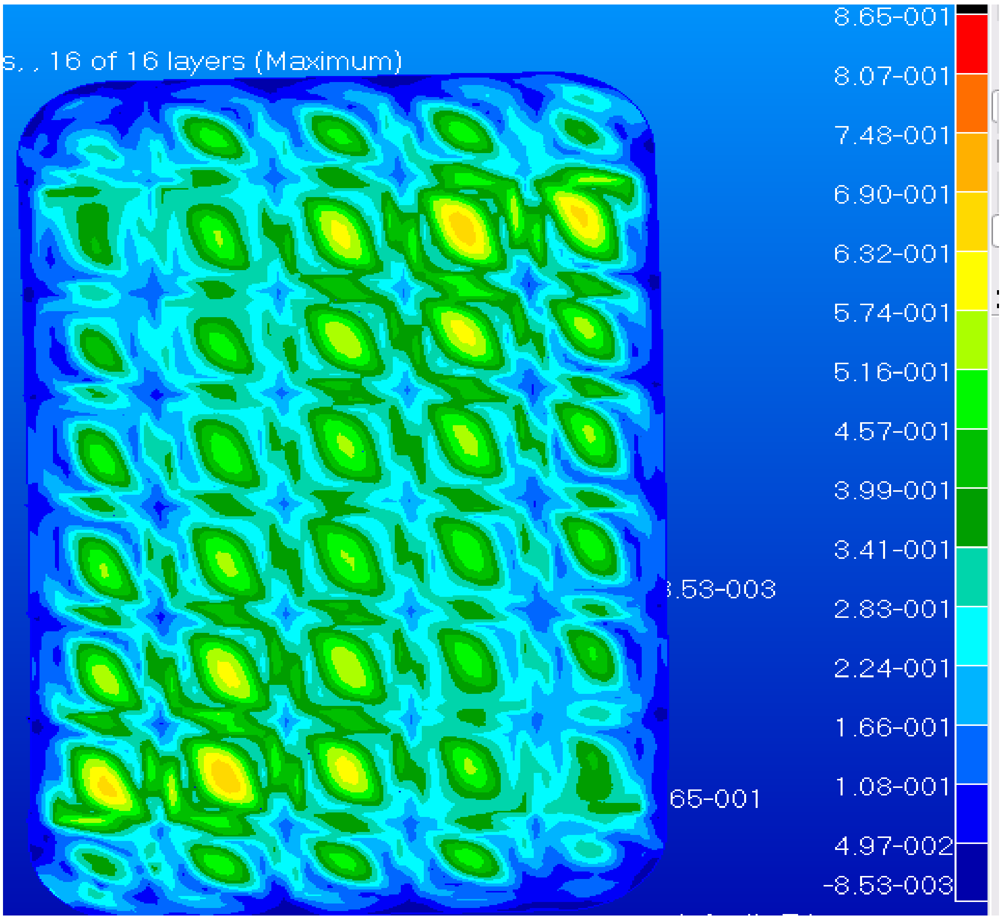


Figure A-10 Failure Indices under $3\Delta P$

Appendix B : GDP WORK

B.1 Introduction:

Our Group Design Project target is to do a concept fly-wing commercial aircraft design of 150-250seats, it was an challenge for us, as known, although the aerodynamic performance is much better than conventional aircraft, there are some obstacles lay before us, for example, the design of pressurized structure and the arrange of the doors according to evacuation criteria of airworthiness, and how to arrange the cabin layout and use lots of the spaces sufficiently for the un-enough height for passenger or containers.

Our project was separated into two stages, the first stage is to design a conventional aircraft, and the second stage is to design a concept fly-wing aircraft following the same procedure and requirements of conventional aircraft.

Figure B-1shows the 3 side view of the conventional aircraft and figure B-2 shows the fly-wing.

Twin-aisle, 250 seats international aircraft.

7500 nm range, M 0.80-0.85 cruise speed

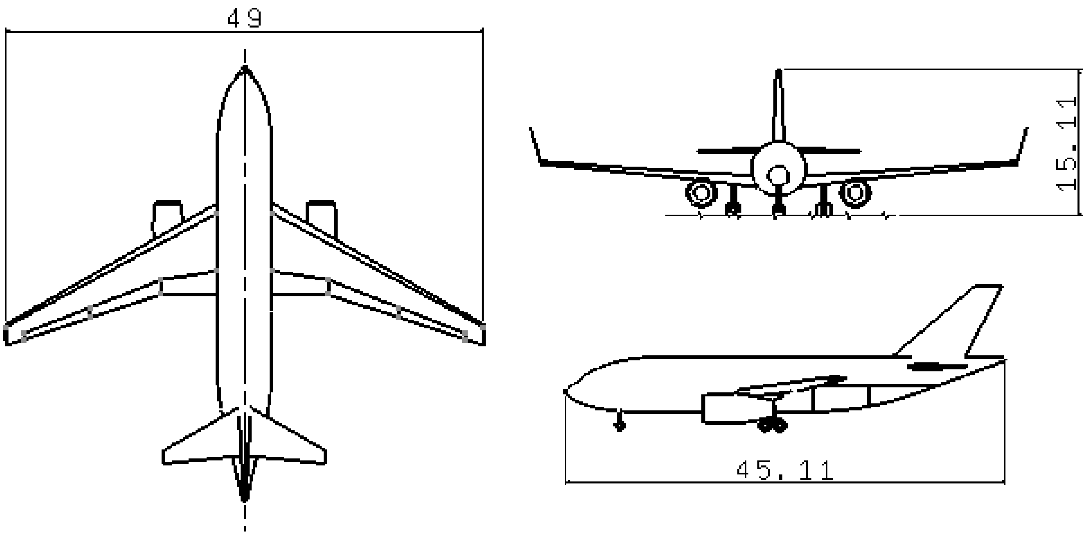


Figure B-1 3-Side View Drawing of Conventional Aircraft

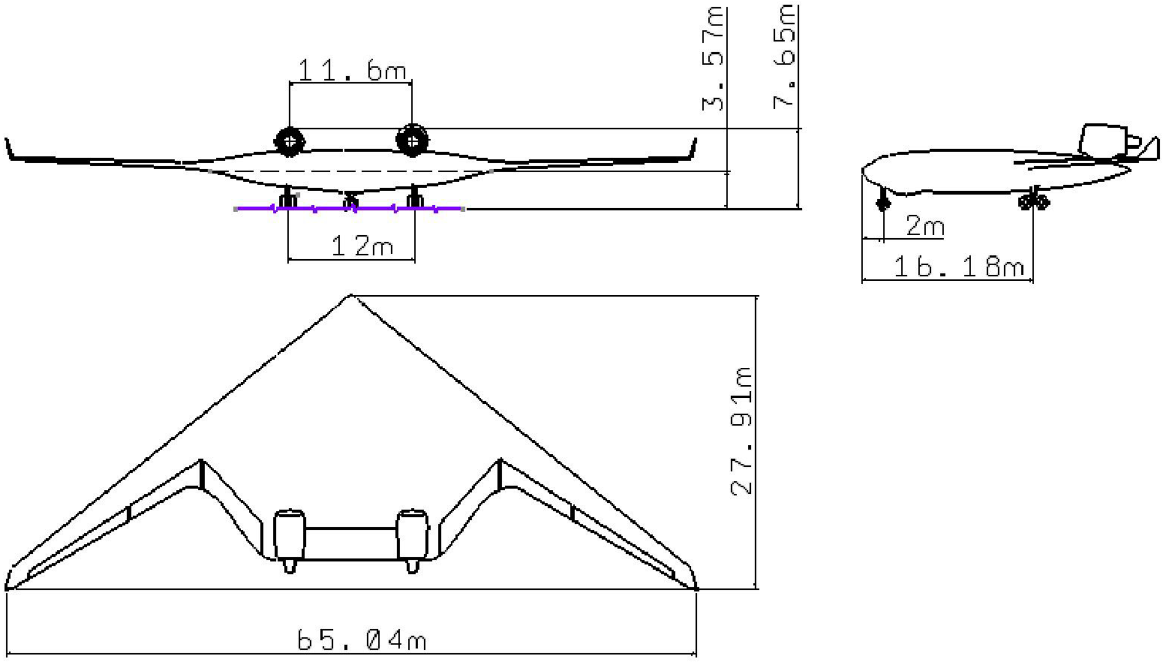


Figure B-2 3-Side View Drawing of Fly-Wing

The contribution of the author to this project is mainly to arrange the doors for this two aircraft which is highly related to the IRP work and it is illustrated in following chapters. Besides the door arrangement, the author's other contributions to GDP work includes as below and will be simply instructed in chapter: B.6.

- The investigation of geometry parameters of 150-250 seats aircraft.
- The family issue investigation
- The cabin layout arrangement
- Drawing 3D model of landing gear

B.2 Airworthiness requirement of doors and evacuation

- FAR 25.783 Doors

(h) Each passenger entry door in the side of the fuselage must qualify as a Type A, Type I, or Type II passenger emergency exit

- FAR 25.807 Emergency exits

(d) Passenger emergency exits. The minimum number and type of passenger emergency exits is in table B-1 as follows:

(1) For passenger seating configurations of 1 to 299 seats –

Table B-1 Minimum Number and Type of Passenger Emergency Exits

Passenger seating configuration (crew member seats not included)	Emergency exits for each side of the fuselage			
	Type I	Type II	Type III	Type IV
1 to 9				1
10 to 19			1	
20 to 39		1	1	
40 to 79	1		1	
80 to 109	1		2	
110 to 139	2		1	
140 to 179	2		2	

Additional exits are required for passenger seating configurations greater than 179 seats in accordance with the following table B-2:

Table B-2 Additional Exits Required

Additional emergency exits (each side of fuselage)	Increase in passenger seating configuration allowed
Type A	110
Type I	45
Type II	40
Type III	35

(7) For an aeroplane that is required to have more than one passenger emergency exit for each side of the fuselage, no passenger emergency exit

must be more than 18·3 m (60 feet) from any adjacent passenger emergency exit on the same side of the same deck of the fuselage.

(e) Ditching emergency exits for passengers

If certification with ditching provisions is requested, For aeroplanes that have a passenger seating configuration of 10 seats or more, excluding pilots seats, one exit above the waterline in a side of the aeroplane, meeting at least the dimensions of a Type III exit for each unit (or part of a unit) of 35 passenger seats.

- FAR 25.809 Emergency exit arrangement

(a) Each emergency exit, including a flight crew emergency exit, must be a movable door or hatch in the external walls of the fuselage, allowing unobstructed opening to the outside.

- FAR 25.810 Emergency egress assists means and escape routes

(1) The assisting means for each passenger emergency exit must be a self-supporting slide or equivalent; and, in the case of a Type A exit, it must be capable of carrying simultaneously two parallel lines of evacuees.

- FAR 25.813 Emergency exit access

Each required emergency exit must be accessible to the passengers and located where it will afford an effective means of evacuation. Where more than one floor level exit per side is prescribed, at least one floor level exit per side must be located near each end of the cabin.

(b) Adequate space to allow crew-member(s) to assist in the evacuation of passengers must be provided.

B.3 Difficult of fly-wing door arrangement

It can be seen from figure B-3, the structure separate the cockpit into four bulbs, 2-2 economy class was arranged, and the cargo area was separated into 2 bulbs each side as well, both the cabin and cargo area are pressurized. The elevator is behind the cabin.

Fly-wing aircraft is a revolution means to traditional aircraft, as it is so different, many facilities and criteria may be also need to redesigned or changed, like the cargo container、the service equipment, the runway, or maybe even the airworthiness. Although many benefits the flying wing has, there are also lots of inherent demerits which are hardly to overcome; the door and evacuation arrangement is one of these. The difficult is including:

- Except the leading edge, there is no side surface for door arrangement,
- It is hard to arrange the floor level doors at the rear of cabin,
- The over-wing emergency exit can't meet the requirement of the step up height.

So, the door arrangement must different from conventional aircraft, but should satisfy the safety requirement.

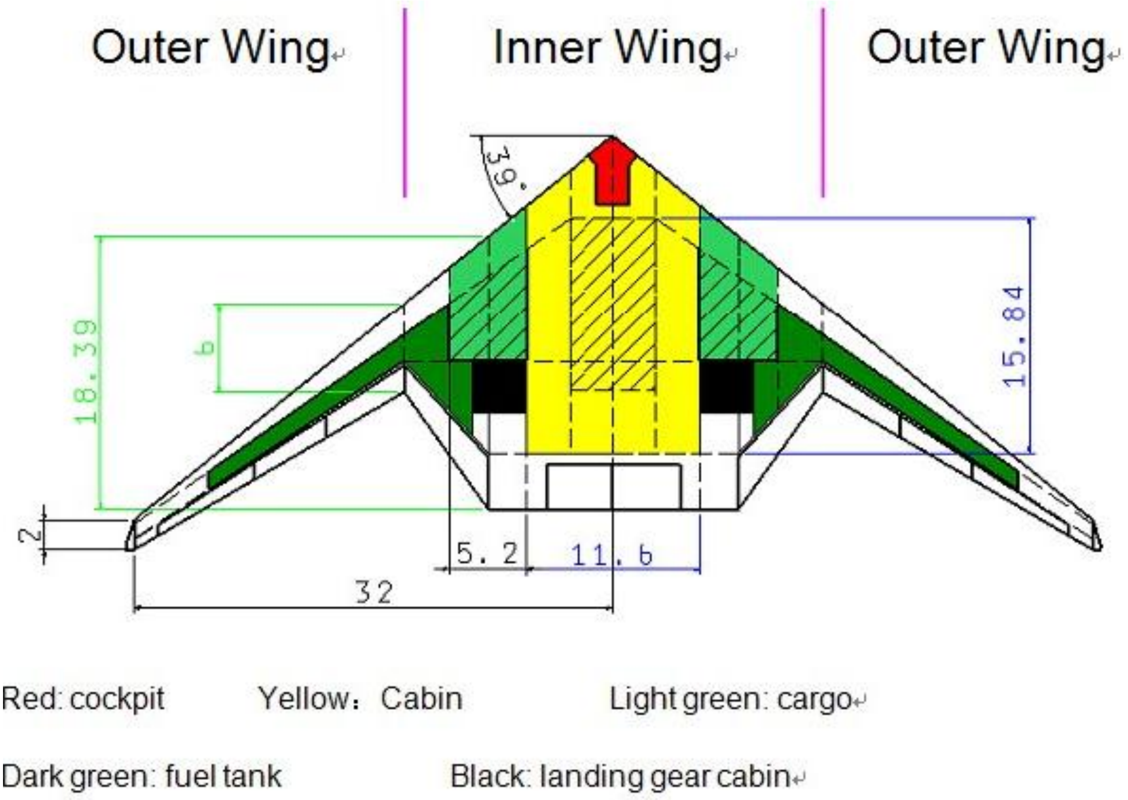


Figure B-3 Flying Wing Geometry and Dimensions

B.4 FW-11 door arrangement

For the fly-wing aircraft, the door arrangement is hard to meet every clause of the airworthiness which is initially established for conventional aircraft, but actually the safety and evacuation ability is the essential issue of the airworthiness, so the door arrangement of fly-wing is based on to meet the requirement of evacuation ability.

- **Passenger door arrangement**

Four type A passenger doors are arranged at the leading edge. Two of them are used for boarding passengers and other two doors are used as service door, and all of them are should follow the emergency criteria of airworthiness.

The passenger doors are applied the plug-type “horizontal slide opening door”. when opening the door first move upward to disengage the stops which are used to keep the door in its position and transfer the pressure load to the fuselage, and then outward and slide parallel to the forward side. The reason for arranging the door opened to the forward is in some extent to prevent the door opening during flight by the aerodynamic load.

- **Emergency exit arrangement**

Four over wing emergency exits are located at the rear part of each bulb, and two located at the front of the two side bulbs. The size of the Emergency exit is arranged as 600 ×800mm which is decide equal to the type Ⅲ exit. As the exits are on the upper surface of the aircraft, a stair with handrail from floor is designed to access each door. The heights of the stairs are between 2.2m to 2.5m.

For the consideration of reliability, the door is designed as plug-type. Because it should not occupy or interference the evacuation path, the inward slide type was proposed, as figure B-4、B-5 shows.

- **Cargo door arrangement**

Two cargo doors are also located on the leading edge, The size is 1200mm× 3010mm to allow the 1100×2200mm container upload.

The cargo door is opened outward and upward rotating a series of hinge, like most of the cargo doors. As figure B-4 shows.

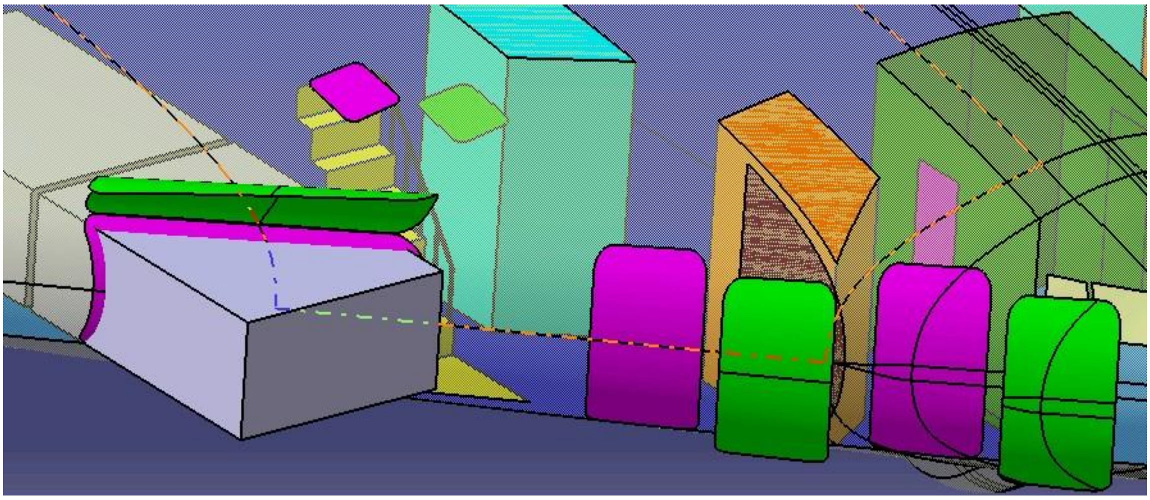


Figure B-4 Doors on the Leading Edge

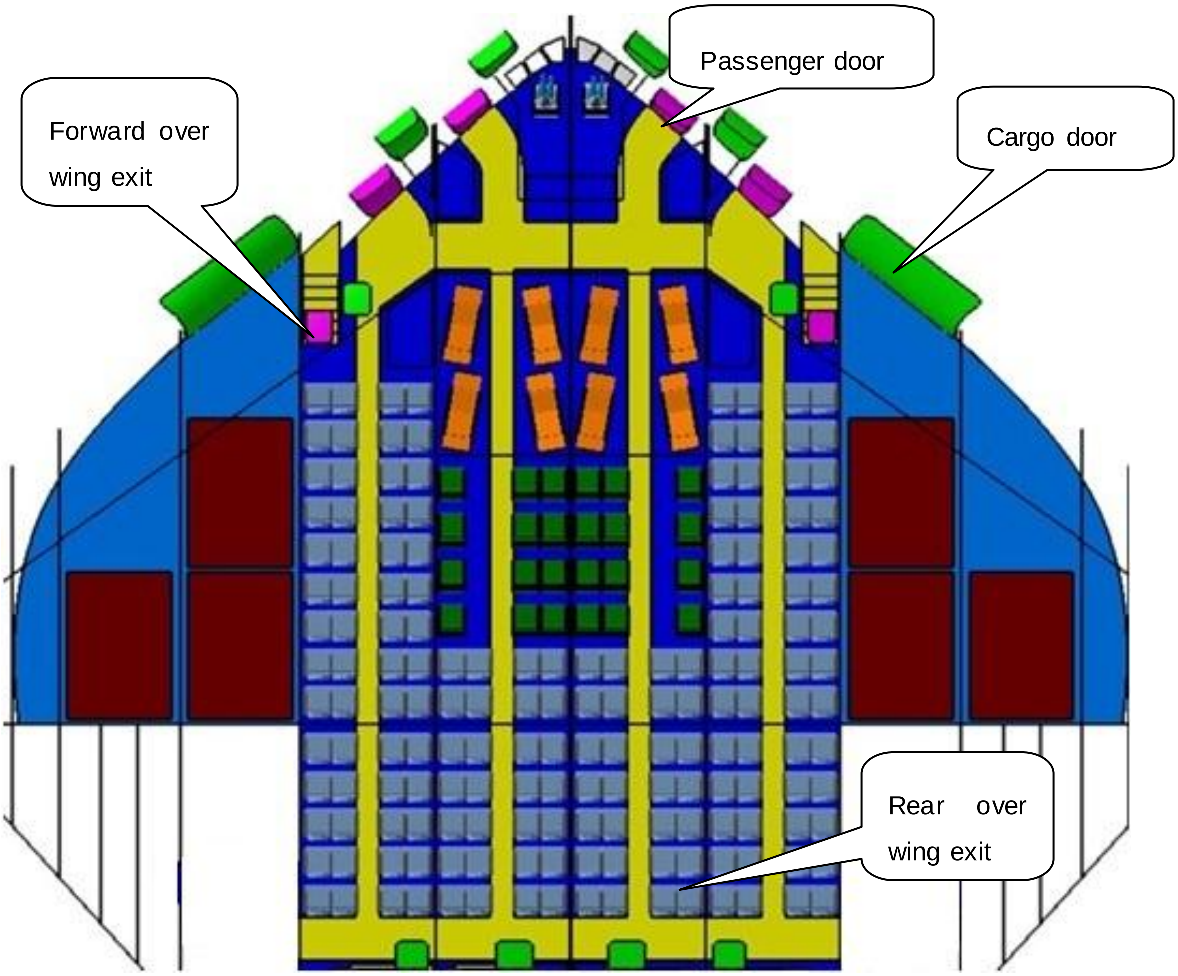


Figure B-5 Layout of the Doors

B.5 Evacuation ability

As the configuration and cabin layout is quite different from conventional aircraft, it is different to satisfy the requirement of the airworthiness, for example it is hard to arrange floor level doors at the rear part of cabin. But as there are 4 aisle leading to the front door which is 2 times than conventional aircraft, the evacuation ability would be better than conventional aircraft, and from table B-3 the total evacuation rate is 440 people in 90s according to airworthiness.

The over wing emergency exits which located in the upper surface can't entirely meet the standard size of typeⅢ exit which is normally in the side surface, as in order to have the same evacuation ability of type Ⅲ exit, finally, the door size is designed as 600×800mm, as figure B-6 shows, and the evacuation clearance can equal to 600×952, which is a little big than type Ⅲ exit. although considering the obstacle of the stairs, it could have the same evacuation ability as type Ⅲ of conventional aircraft, it is allows 35 people to escape within 90s.

So, the total evacuation ability should be 650 people within 90s and 325 people for half of the doors can't open, as table B-3 shows. So the evacuation ability can meet the airworthiness requirement.

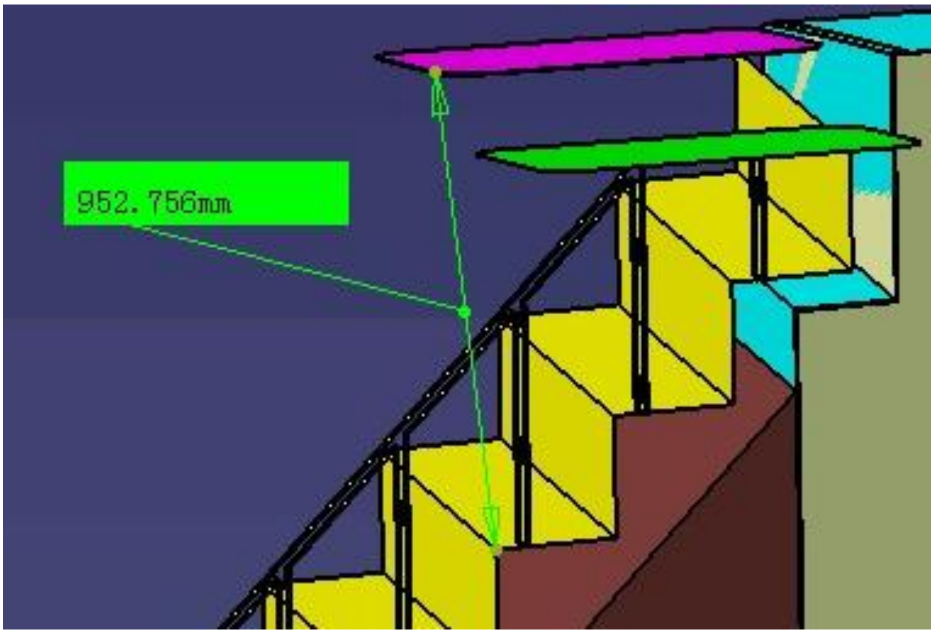


Figure B-6 The Evacuation Clearance

Table B-3 Arrangement of FW-11 Doors

name	type	size(mm)	number	evacuation ability (people/90s)	
CABIN area					
passenger door	type A	1070×1830	4	110	
forward over-wing exit	N/A	600×700	2	equal to 35	Totally 650
rear over-wing exit	N/A	600×800	4	equal to 35	
CARGO area					
cargo door	N/A	1200×3000	2	N/A	

B.6 Other contributions

B.6.1 The geometry investigation

At the beginning of GDP, the target is to do comprehensive survey of the geometric characteristics of existing 150-250 seat aircraft. The survey includes the aircraft structure format, geometry parameters, structural materials etc., and the geometry database is shown in table B-4 while the material survey can be seen in figure B-7 to figure B-9.

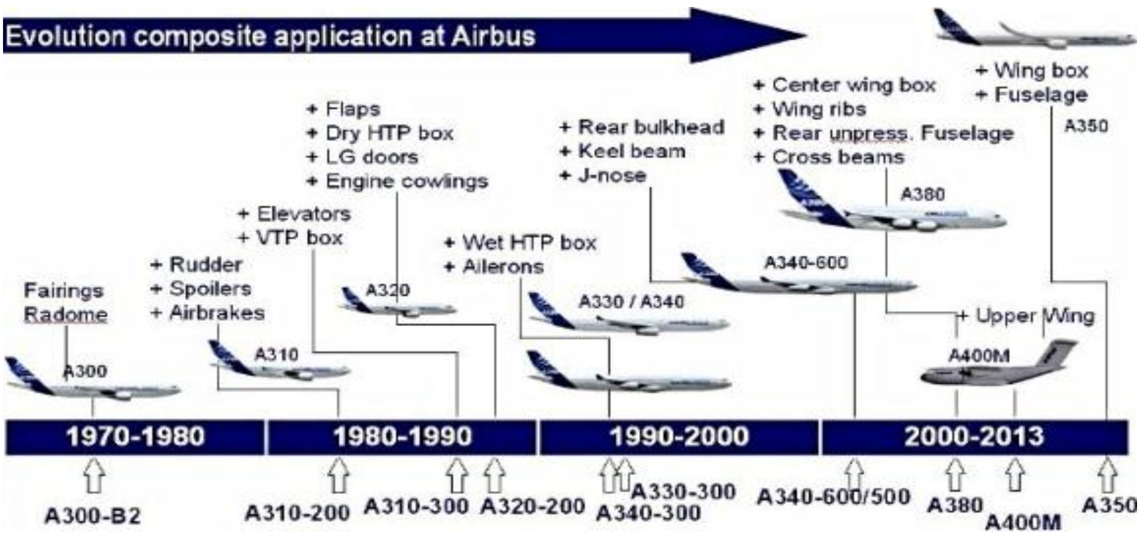


Figure B-7 Evolution Composite Application at Airbus [29]

During the past 30 years, AIRBUS has continuously and progressively introduced composite technology as a consequence of successful experience accumulated.

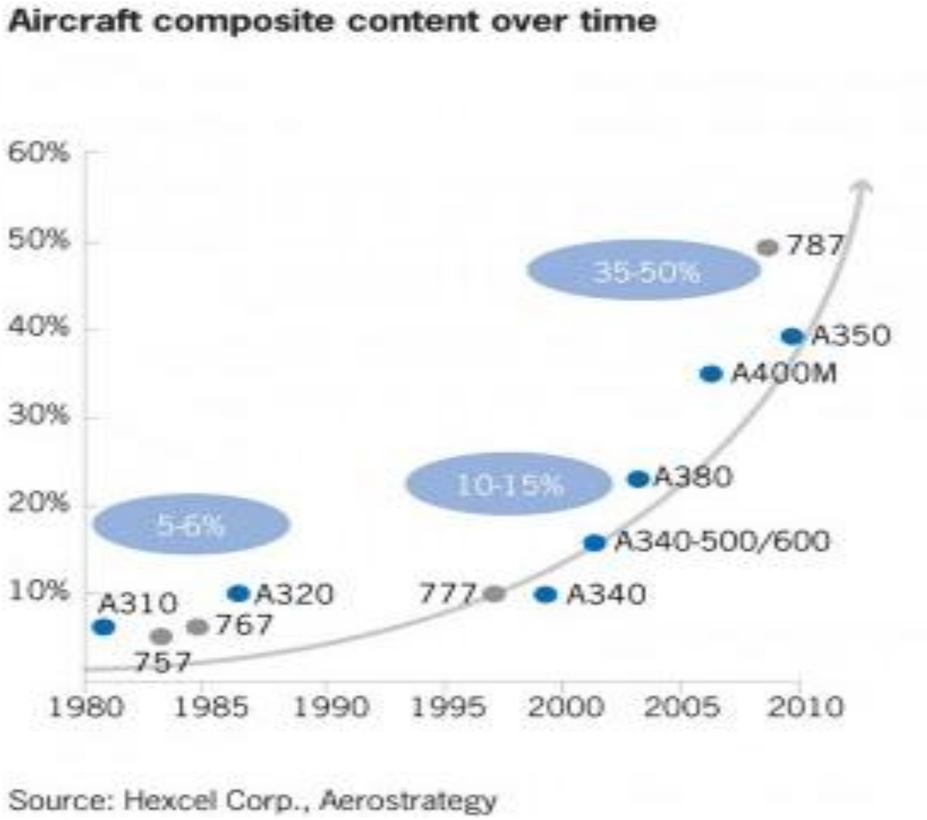


Figure B-8 Aircraft Composite over time [30]

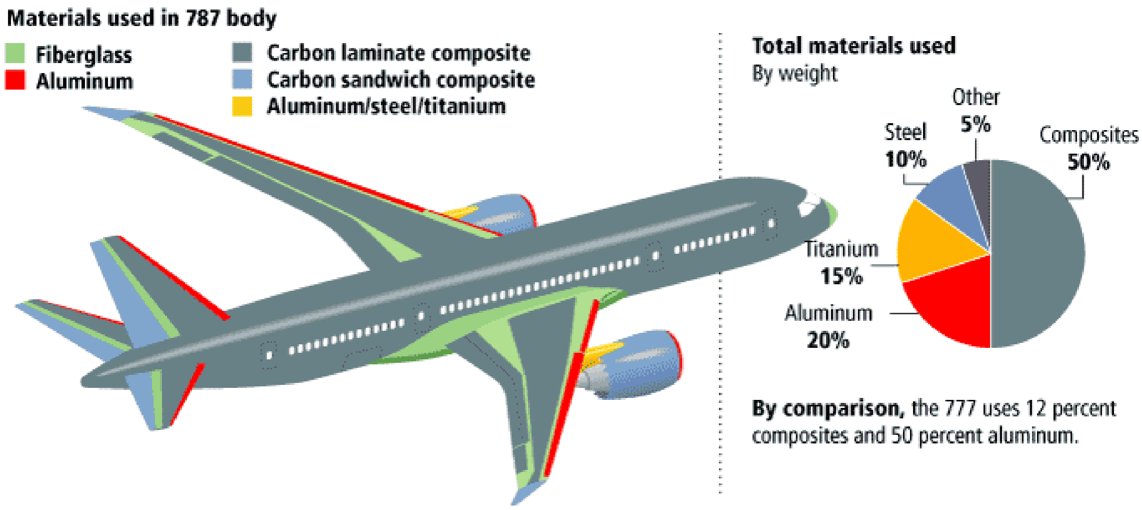


Figure B-9 Composite Application of B787 [30]

Table B-4 Geometry Database [27] & [28]

AVIC-4 Geometric Design GDP Survey Database												
Conventional aircraft												fly wing
COUNTRY			USA					INTERNATIONAL				USA
Manufacturer							McDonnell	AIRBUS				Northrop
Type			737-800	757-200	767-200	787-8	MD-90-30	A319-100	A310-300	A320-200	A321-200	B2
Geometric	seats(max)		160-189	200-234	181-290	210 - 250	153 to 172	160	240	180	220	/
	Wing area(m2)		124.6	185.25	283.3	325	112.3	122.6	219	122.6	122.6	465.5/5010.60sq ft
	wingspan(m)		34.3	38.05	47.6	60	32.87	33.91	43.9	33.91	33.91	52.1/171ft 11in
	sweepback(quarter chord)(º)		25	25°		32.2	24.5	25	28	25	25	33
	Vertical tail surface(m2)		23.13	34.37	46.14		21.4	21.5	45.2	21.5	21.5	/
	Horizontal tail surfaces(m2)		32.4	50.35	77.69		33	31	64	31	31	/
	t/c=thickness to chord ratio(%)				11.5		11		11.8			/
	fuselage geometry	Length (m)	38.08	46.96	47.24		43.00	33.84	45.13	37.57	44.51	20.9/69ft 7in
		Height (m)	3.73	4.10	5.03		3.61	11.76	5.64	11.76	11.76	5.1/ 17ft 9in
		Width (m)	3.73	4.00	5.03		3.61	3.95	5.64	3.95	3.95	
		Finess Ratio	7.40	11.74	9.39		11.91	8.56708861	8.00	9.5113924	11.2683544	
	landing gear and clearance (undercarriage)	Track (m)	5.7	7.32	9.30		5.09	7.6	9.60	7.6	7.6	
		Wheelbase (m)		18.29	19.69		23.53	12.6	15.21	12.63	16.9	
		Turning radius (m)		36.60	39.30			20.6	31.40	21.9	29	
		No. of wheels (nose; main)	2;4	2;8	2;8		2;4	2;4	2;8	2;4	2;4	2/4
		Main Wheel diameter (m)	1.016		1.143			1.143	1.168	1.143	1.27	
		Main Wheel width (m)	0.368		0.432			0.4064	0.406	0.4064	0.455	
		Length (m)	4.70	5.2	6.22		5.75	4.44	6.30	4.44	4.44	
		Max. width (m)	2.06	2.60	2.68		1.55	2.37	2.70	2.37	2.37	
		Span wise	0.282	0.34	0.324		-	0.338	0.352	0.338	0.338	

		type	CFM56-7B24	RB211-535E4B	CF6-80A	General Electric GEnx /Rolls-Royce Trent 1000	IAE V2525-D5	**P&W PW6122**	**4152.0**	**CFM 56-5A**	**CFM56-5 or IAE V2500**	F118-GE-100/4
		size	2	2	2	2	2	2*102kN		2*104kN	2*120kN	len=2553 dia=1181
		location	under-wing	Under-wing	Under-wing	Under-wing	rear fuselage	Under-wing	Under-wing	Under-wing	Under-wing	back of wing
		thrust reverse						2*102kN		2*104kN	2*120kN	77

B.6.2 The family issue investigation

The advantage of family design is apparent, because of the similar design, with far less investment of money and time on the research and development of a new aircraft, the aircraft manufacturer can easily and quickly produce an aircraft according to the needs of the aviation market. When manufacturing the airframe or parts of the aircraft, the tooling cost, material cost and equipment could be reduced dramatically. [31] Therefore, Boeing and Airbus Company designed many aircraft based on family.

A successful aircraft family of Boeing is the B737, it has developed into a family of nine passenger models with a capacity of 85 to 215 passengers.The Boeing 737-100, 737-200, 737-300, 737-400 and 737-500, are relative old types in this family. Under the competitive pressure of Airbus A320 family, Boeing launched the 737 Next Generation (737-600, 737-700, 737-800 and 737-900 series) program in early 1990s with multiple changes including a redesigned wing, upgraded cockpit, and new interior. From figure B-10 it can be seen the derivation method.

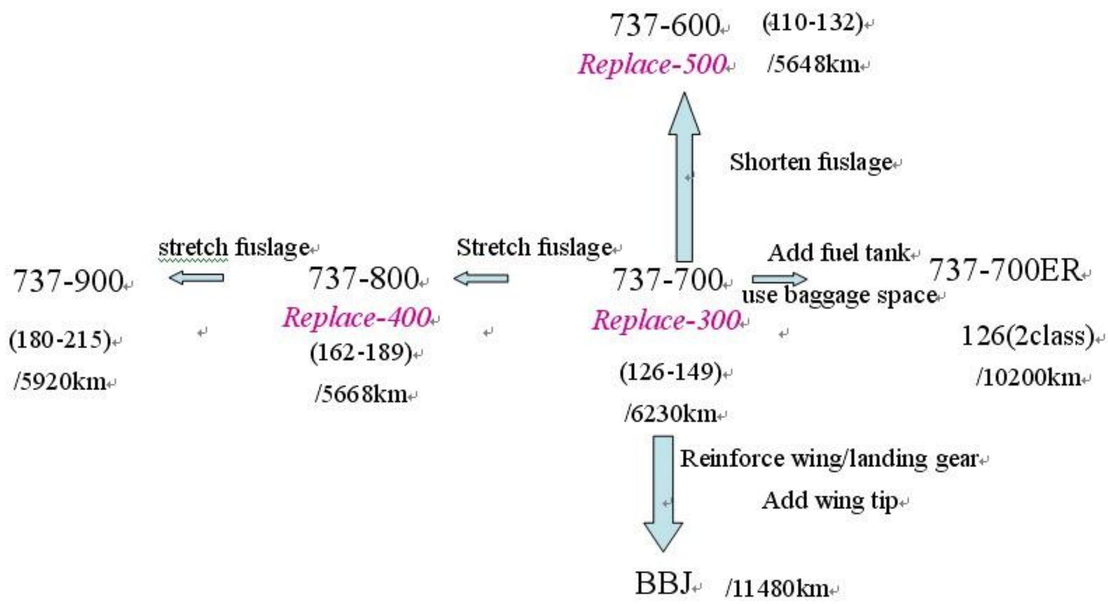


Figure B-10 The Derivation of 737 NG

A320 family is a successful product of Airbus, There 4 types of aircraft in this A320 family: A318, A319, A320 and A321. The seats and range of these 4 types are shown in Figure B-11. They share the same wing、fuselage、cross section and very similar cockpit.

Figure B-11 Airbus A320 Family Seats and Range [32]

For the fly-wing, it is divided into a pair of wings, which all include the outer wings and inner wings. Once the wing span is changed, the spars of the wing will be changed accordingly.

B.6.3 The cabin layout arrangement

According to investigation, comparison and analysis, the cabin accommodation capacity should be 200 seats in 3 class layout.

Typical configuration： 200 in mixed class

Internal cabin width： 5.30m (4 compartments)

Seating abreast： 4(2-2) for economy class

Passenger door: 4

Lavatory: 4

Galley: 2

Closet: 3

B.7 Conclusion

The Group Design Project is an important part of MSc design study besides IRP, it lasts nearly half years and we have completed Fly-wing concept design. For details can be seen in "FLYING WING AIRLINER FW-11PROJECT SPECIFICATION". According to the GDP work, I have widely broadened my Professional knowledge and can have an overall view consideration of aircraft.